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A REVIEW AND COMPARATIVE STUDY OF SOME SURFACE GEOPHYSICAL  
METHODS APPLIED TO THE INVESTIGATION OF LANDFILL SITES

BY

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This thesis is submitted in partial fulfilment of the  
requirements of the CNAA degree of Master of Philosophy

Sponsoring Establishment: Middlesex Polytechnic  
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July 1987

A REVIEW AND COMPARATIVE STUDY OF SOME SURFACE GEOPHYSICAL  
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A REVIEW AND COMPARATIVE STUDY OF SOME SURFACE GEOPHYSICAL  
METHODS APPLIED TO THE INVESTIGATION OF LANDFILL SITES

BY ANDREW ROBERT COLEMAN

ABSTRACT

This report presents the findings of a comparative study of the effectiveness of geophysical techniques in the ground investigation of a landfill site. Part I of the report introduces the topic with a comprehensive introduction which includes a review of the nature of landfill and an explanation of the need for the investigation requirement.

Part II describes trials using various geophysical methods to determine the position of a landfill boundary and its depth. It includes a review of similar applications reported in the literature. The geophysical methods were evaluated on a reclaimed domestic refuse tip formed in a sand and gravel quarry, at Panshanger near Welwyn Garden City, Hertfordshire.

The methods employed were, seismic refraction, resistivity traversing and sounding, electromagnetic induction traversing and sounding, ground self potential traversing, magnetometer traversing and ground radar traversing.

The report concludes that all the methods tried located the boundary, but that electromagnetic induction traversing and magnetic traversing are most successful in determining the boundary position precisely and are also quick to use.

Quantitative interpretation of the depth of fill and dip of the boundary using resistivity sounding and seismic refraction surveys was not so successful; in the former case, due to insufficient resistivity contrast between the fill and the base material, and in the latter, due to poor energy propagation through the fill.

Recommendations for the application of suitable methods to other categories of filled sites are given.

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A COMPARATIVE STUDY OF SURFACE GEOPHYSICAL METHODS FOR SITE  
INVESTIGATION OF LANDFILL SITES

PART I

AN INTRODUCTION TO THE TOPIC

1      The development of the landfill method of waste  
disposal

Waste disposal by burial is the most common method of refuse disposal in the United Kingdom; 85% of domestic refuse is disposed of in this way (Skitt 1979). The method utilises the space available in disused quarries, or occasionally in natural depressions, for the containment of refuse. The burial sites may be subsequently reclaimed by covering with a suitable capping material, topsoil, and then landscaped and planted.

The concept of disposal by burial is not new. The middens of prehistoric settlements are an early example. More recently, moats and defensive ditches were used to receive rubbish when they were no longer required for their original purpose. Convenient holes in the ground, man-made or natural, situated near to settlements have been used as rubbish tips, probably since man started to live in permanent communities. This type of uncontrolled waste disposal by burial has continued well into this century.

Landfill is a larger scale operation which is subject to statutory controls. The Public Health Act 1936, (Section 76 1) states "A local authority may provide places for deposit of refuse." The Town and Country Planning Act 1971 (Section 22) requires planning permission to be obtained for any development which, amongst other things, results in a "material change of use of any buildings or other land". (The section specifies that a material change of use has occurred if the deposition of waste or refuse on land already used for that purpose results in the extension of the deposit or an increase in its height above the surrounding land). Under this Act, the waste disposal aspect may be part of another activity. For example, planning permission may be granted for the extraction of a mineral on the condition that the quarry is backfilled (with waste) and is restored to its original condition.

The Control of Pollution Act 1974 (the 1974 Act) has placed further constraints on the deposition of waste. The concept of "Controlled Waste" was introduced, being household, industrial or commercial waste, but excluding mine or quarry waste, agricultural waste and sewage. The Act (Section 2) designates Disposal Authorities responsible for the planning of the disposal of Controlled Waste. These Authorities also issue Disposal Licences (Sections 3-11). Planning permission is still required as a prerequisite of the Licence. The conditions to be satisfied prior to granting a Licence also require a plan of the proposed site to be submitted with indications of the proposed volume and type of waste.



The method of tipping of domestic and industrial waste by Local Authorities has tended to be relatively more controlled than the smaller scale private disposal. The Annual Report of the Ministry of Health in 1931-32 published a series of guidelines for the tipping of domestic and industrial wastes. These guidelines were embodied in the Department of Environment Code of Practice issued by the Working Party on Refuse Disposal in 1971 and later in the licencing conditions of the Control of Pollution Act 1974. The primary objective of the guidelines appears to be to ensure that refuse is not allowed to be wind-blown or washed away from the tip, and that the site is kept as tidy as possible. However, the following guidelines improve the degree of compaction and homogeneity of the fill:

"Refuse should be formed into a layer as soon as possible after tipping and not later than the end of the working day on which it is received.

"The layer of refuse should be formed so that it does not exceed 8 feet (2.44 m) in depth after initial compaction. Where the material tipped is pulverised refuse, it may be necessary to restrict the depth of layer to 4 feet (1.22m) after initial compaction on some sites close to development.

"As tipping proceeds (and not less frequently than at the end of each working day) all tip faces and flanks should be consolidated and formed to a gradient not steeper than one in three by driving the tractor up and down the tip

face.

"The tipped material should be covered progressively so that all surfaces, including the tip face and flanks, are covered at the end of each working day with a layer of suitable sealing material, spread so that it is not less than 9 inches (229 mm) thick, except that the thickness of covering material on layers formed solely of pulverised refuse need not exceed 6 inches (152 mm).

"All large articles, such as furniture or hollow containers, should be tipped in front of the tip face. They should be crushed, broken up or flattened by the tractor and covered each day by other refuse, in such a position that they are not within 3 feet (0.91 m) from the tip faces and flanks."

The usual method of tipping in this country is by end tipping from the top (Skitt 1979). Skitt describes a process by which the lowest part of the quarry is filled first and layers 6 feet (1.82 m) deep are built up by end tipping. Each layer is in the form of lobes or bays 40 feet (12.20 m) wide, separated by gaps 40 feet wide, which are subsequently filled. He recommends that the bays of subsequent layers are not formed directly over the preceding bays to avoid uneven settlement. Each layer is sealed with a suitable cover material. The size of bays and depth of each layer will vary from tip to tip. A tip formed in this fashion will comprise layers of refuse separated by thin

seams of cover material with sloping boundaries separating each bay.

The Mines and Quarries (Tips) Act 1969 is concerned with the disposal of inorganic waste from mines and quarries. Part 1, Section 6 of this Act requires the preparation of plans and sections of the proposed tip.

Despite the controls referred to above, there are many old waste tips where the boundaries and depths of the fill are uncertain. The existence of smaller tips may even have been forgotten. The extent and depth of those tips which do come under the controls mentioned above may not conform to the positions indicated on the plans. The plans are produced prior to tipping and are not necessarily designed as an accurate record of what was constructed.

There are two types of sites which may be termed landfill in the broad sense. The first type are typically small quarries, pits or natural depressions which have been filled intermittantly with a variety of materials from a variety of sources, much of which was from fly-tipping. They can occur anywhere there is a suitable hole in the ground. Since they were essentially an ad-hoc development, their location and content were not affected by statutory controls. It is, therefore, this type of tip which will require the most investigation because its shape, size and content are likely to be unknown. These tips are usually smaller than the second type, which are now generally referred to as landfill sites.

Landfill sites are frequently filled with a material of one type, as a deliberate policy, by one organisation which is responsible for the tip. They may be operated by companies which use them to dispose of a waste by-product of their main activity; for example, an open-cast coal pit may be used to receive slag from later mining. They may be operated by companies or local authorities which collect and dispose of industrial or domestic waste. They are often now "engineered" with regular cells contained by bund walls which introduces a further degree of uniformity.

Landfill sites have been subject to statutory controls, as described previously, although the degree to which the various provisions were enforced probably varied greatly

until the passing of the 1974 Act. The selection of suitable landfill sites will have been influenced by the guidelines and controls, so that their location is not determined only by the availability of quarries and pits. The current factors which affect the selection of suitable sites are listed in "Waste Management Paper No. 1", published by the Department of the Environment (1976). They are:

- a) The types and quantities of waste to be delivered to the site, in relation to its capacity.
- b) Possible ground or surface water pollution.
- c) The adequacy of access to the site by road, rail or water.
- d) The possible affect on the inhabitants, wildlife and amenities of the area.
- e) Traffic congestion.
- f) The planned after-use of the site; the amount of landscaping, modelling, top-soiling and planting necessary.
- g) The enhanced value of the land when reclaimed.
- h) The estimated capital and operating costs of the scheme.

The quarries which have been considered to be suitable for landfill tend to be concentrated near to, or in, older urban areas. This is because, in the north of England in particular, coal, ironstone and limestone quarries were excavated to provide the raw materials for the early basic industries around which other industry developed. However, claypits, excavated to provide raw material for the brick industry, can occur in isolation and are particularly suitable for landfill sites owing to the low permeability of the host material. The Mercia Mudstone and Oxford Clay are typical examples.

In the south east of England the majority of landfill sites are in aggregate quarries, chalk quarries and clay pits. None of these have been the cause of the development of industry around them, but aggregate quarries have been excavated near to urban areas.

This juxtaposition has arisen because aggregate quarries are worked in Pleistocene and Recent deposits of sand and gravel. River valley gravels are accessible because of their minimal overburden cover, thus making them attractive to the aggregate industry which has extensively quarried this source of aggregate. Glacial outwash sands and gravels are often exposed in the sides of valleys beneath a cover of till. A second source of gravel is therefore available in the major valleys. These valleys tended to contain the main routeways along which urbanisation spread especially in the vicinity of London. Thus the coincidence of location of urban areas and sand and gravel aggregate quarries developed.

There are two reasons for investigating landfill sites. Firstly, information may be required which gives an indication of the pollution threat of the site. The nature and amount of fluids emitted from the fill would be of interest and the investigation would form part of a hydrogeological study. Secondly, information may be required which would enable the site to be assessed as building land. This may also include a requirement to determine the pollution potential. In both cases it is likely that time-effects would be considered, but this monitoring requirement will not be considered further here. This second objective is commonly referred to as "Site Investigation" and will be the term used in this study. The preferred term according to the Code of Practice for Site Investigations, B.S. 5930: 1981, is "Ground Investigation", Site Investigation being investigation in the wider sense, which includes the Desk Study stage.

The interest shown in building on landfill sites has arisen from inter-related factors. Firstly, the increase in population with the concomitant increased demand for housing and office and factory accommodation, has made what was previously marginal building land, including landfill sites, more attractive.

Secondly, the development of the industrial and consumer society has resulted in an increase in the amount of refuse created by industry and individuals. Since landfill is the

most common waste disposal method in the United Kingdom, the rate of production of landfill sites has increased. The existence of quarries suitable for landfill, in or near urban areas, has meant that eventually the reclaimed landfill sites are considered as economic building land.

Finally, the increase in construction work, resulting from the increase in population and urbanisation, has created a higher demand for aggregates. In the south east of England the aggregate is obtained from the Pleistocene and Recent sands and gravels. New quarries are excavated which, as previously noted, have tended to be concentrated near urban areas. Subsequently, they become landfill sites which are considered as economic building land. (However the latest trend is to site quarries in rural areas away from residential areas.)

Construction on landfill is becoming more common. Industrial development is more frequent than domestic, partly because higher rates of settlement can be tolerated with suitably designed units. However, in Dudley, West Midlands, houses have been built on fill comprising a mixture of mining, industrial and domestic refuse (Gilbert and Knipe 1979) and in Manchester, the Local Authority developed a housing site on fill comprising ash, brick and demolition rubble (Gray and Thomson 1979).



The objectives of a site investigation of a landfill site fall into three categories; the determination of its size and shape, its chemical composition and its physical characteristics.

The first objective entails a determination of the landfill boundary position; the boundary in this sense being the three dimensional surface between the waste material and its host material.

The boundary position affects the choice of foundation type. The choice is relatively straight forward for buildings positioned either wholly on or off the filled area. However, the position and angle of dip of the boundary surface becomes a critical factor in the foundation design of those buildings positioned near to the margin of the landfill, because buildings on the filled area would most probably have a different foundation type from the buildings beyond the margin of the landfill. The angle of dip of the boundary surface is important because it determines the amount of excavation required to reach the host material, which in turn determines whether, for a given position, an off-tip or on-tip foundation is required.

The second objective, the determination of the chemical characteristics of a landfill site, should reveal the presence of chemicals which may be aggressive to building materials, which are combustible, or which may evolve toxic

or combustible gases (Smith and Russel 1983). In addition, it is necessary to identify materials which are chemically unstable and which, by decomposition or alteration, could change the physical condition of the waste. For example, settlement would result from the decay of organic materials (Harris 1979).

The third objective, the determination of the physical characteristics, provides information that enables an assessment of the bearing capacity and settlement characteristics on which the foundation is based. The methods available are Plate Loading Tests to determine bearing capacity and settlement characteristics, and Standard Penetration Tests to give an indirect assessment of the bearing capacity. However, the latter relies on empirical relationships developed for granular soils; the validity of their application to landfill is doubtful.

The sampling and testing frequency on a landfill site has to be sufficiently high to give a representative range of results, on what is characteristically a variable material. Carpenter et al (1985) have indicated sampling frequencies for various sizes of site. They recommend that the minimum number of trial pits should be; 5 for a 0.5 hectare site, 9 for a 1.0 hectare site and 20 for a 5.0 hectare site. Each pit should be 3.0 m deep and 2 kg samples obtained from depths of 0.15 m, 0.5 m, 1.0 m, 2.0 m and 3 m. They stress that more frequent trial-pitting and sampling should be undertaken if the ground is particularly variable.

In-situ tests which can only be carried out at the surface have limitations. Harris (1979) performed plate loading tests in shallow excavations on landfills comprising pulverised waste and untreated waste. He reported difficulties in securing the reaction beam to the loose fill and in the provision of a sufficient travel on the screw jack which applied the load. These problems were a consequence of the relatively poor compaction of the fill, but they can be overcome usually by using kentledge, or a lorry to provide the reaction.

The diameters of the loading plates used in Harris's investigation were 316 mm and 460 mm. The depth of material tested in this example was less than 1.2 m, if it is assumed that the depth of ground significantly stressed, by the application of loads on these plates, is 2.5 times their diameters (Tomlinson 1973). Harris also points out that the surface layers are likely to have different properties from the bulk of the fill because they will have decomposed aerobically and rapidly, whilst the remainder of the fill will have been partially decomposed under anaerobic conditions. It also seems likely that there would be an increase in density, with depth, resulting from compaction caused by the self-weight of the fill.

It is the deeper layers of fill which are of interest to the foundation designer, as it is these that will influence the bearing capacity and settlement characteristics. The limitations of small diameter plate loading tests can only be overcome by increasing the size of the plate, which is

not always practical, or by placing the plates in the base of boreholes, which may not be safe if the tip is toxic or chemically unstable.

The current objectives and procedures for investigation of landfill sites are mentioned briefly in Appendix E of B.S. 5930 : 1981. Section E.3.3. states that investigations should be carried out to determine the depth and extent of backfilled workings. It points out that although the extent of backfilled coal and ironstone workings may be well documented, the limits shown on mine abandonment plans may be those of the seam area extracted and not the limit of the pit. It goes on to say that smaller mineral workings may not be so well documented. The code also states that an investigation should include a study of the chemistry of the waste if the presence of industrial waste is suspected.

The first requirement, that of boundary location, could be achieved by a combination of excavation and drilling with geophysical methods to provide interpolation between the excavations. This is a common practice in surveys of many naturally occurring geological boundaries. The present study is directed at determining which geophysical methods could be used to achieve this aim on a landfill site.

The boundaries of landfill are often irregular, either as an original feature of the quarry, or resulting from slumping subsequent to excavation; the refuse is inhomogeneous, often containing metal, buried bund walls, access roads and water. All of these characteristics make the interpretation of

geophysical surveys difficult, but they also make interpolation between excavation more necessary for an accurate assessment of the boundary.

It is possible that geophysical methods could be used to provide additional information on the physical and chemical characteristics of the waste as part of a monitoring programme, but this aspect is not dealt with in this study.

Previous research into the application of  
geophysical survey techniques to the investigation  
of landfill sites

Of the two objectives of landfill investigations (the assessment of potential pollution and the feasibility of construction) most research has been carried out on the pollution aspect. Research into the application of geophysical techniques has concentrated on electrical methods, particularly resistivity.

Cartwright and McComas (1968) used electrical resistivity profiles taken around a landfill site in Du Page County, Illinois, to construct an iso-resistivity map which, they were able to show, correlated with the concentration of chloride in the leachate. The host material for the Du Page County landfill site is described as Pleistocene glacial deposits which comprise 10 feet of "surficial glacial outwash materials, which are mainly fine silty sand" overlying glacial tills.

They found that the apparent resistivity of the glacial outwash sand was 26 to 30 ohm-metres, but adjacent to the fill, where the concentration of leachate was highest, the resistivity was 2 to 5.5 ohm-metres. They inferred that lobes of low resistivity material which extended from the landfill were caused by movement of leachate into the surrounding sand.

Cartwright and McComas (op. cit.) also attempted a correlation between resistivity values and concentration of sodium chloride by measuring the chloride concentration in borehole samples of water and establishing a relationship between these values and the resistivity measured in the field. They found that there was a linear relationship between the two parameters over the relatively small range of values encountered, although they point out that over a larger range the relationship should depart from a straight line.

Similar work was reported by Finch (1979) who was able to map the leachate around a colliery spoil tip in the Bunter Sandstone of Nottinghamshire. He was also able to obtain three dimensional information on the shape of the contaminant by using resistivity soundings to construct geoelectrical sections. These showed the depths from which the leachate was issuing from the landfill.

Other reports of the application of electrical resistivity surveys to the delineation of leachate include; Warner (1969), Stollar and Roux (1973), Rodrigues (1976), Knight et al (1978) and Nunn (1979). Klefstad et al (1975), listed a number of limitations of the resistivity technique when used to map leachate. They found that the most widespread difficulty arises from the variation in lithology of the material containing the leachate, which can mask the variation in resistivity arising from the distribution of leachate. They also found that the resistivity values were very sensitive to the material at shallow depths.

The use of electromagnetic induction (E.M.) as a means of obtaining measurements of apparent conductivity has been widely reported since the introduction of the portable range of instruments manufactured by Geonics Ltd.

The method has been used to assess the position and movement of leachate plumes and reports often compare the results from conventional resistivity surveys with E.M. surveys. The values of conductivity are commonly converted to resistivity. Benson and Glaccum (1980) were able to trace a plume seven miles from its source using E.M. Slaine and Greenhouse (1982) showed that the results of E.M. surveys could be contoured to indicate the relative concentrations of leachate surrounding landfill and leaking lagoons. They pointed out the need for geological control so that an estimate of the likely apparent conductivity could be obtained, which enables the identification of the anomalous conductivity values. Glaccum et al (1982) were able to monitor the movement of leachate plumes by taking successive surveys across the contaminated area. They found that the speed at which the E.M. equipment could be used to gather data, enabled readings to be taken at a high density, thus providing more detailed information than resistivity surveys.

In 1983, Glaccum et al, recognising the nonlinearity of the response of the E.M. equipment at high conductivities, reported a survey in which they had corrected data for surveys across leachate plumes. Correction curves exist, but refer to ground which is equivalent to a homogenous half



space, which was not the condition prevailing on the site they were investigating. Glaccum et al (1983) applied the correction, however, and found that the conductivity values obtained with the E.M. equipment agreed closely with those derived from resistivity traverses. The corrected readings were in the range 10 to 350 mmhos/m (1100 to 3 ohm/m).

The E.M. technique has been used to detect other conductive bodies of water. Cameron, De Jong, Read and Oosterveld (1981) investigated the extent of salt water encroachment into arable land and found a linear relationship between true soil conductivity and their E.M. readings, although the exact relationship varied from site to site. Stewart, 1982, mapped the saltwater interface using E.M. in a coastal region of Florida and found the equipment more sensitive than conventional resistivity methods. Ladwig, 1983, used the method to successfully detect the existence of acid mine drainage. He estimated that the E.M. surveys could be performed approximately four times quicker than conventional Wenner resistivity surveys. A similar survey was carried out earlier by De Jong et al in 1979. The principle of using differences in conductivity as the measurement parameter is therefore well established for landfills, but its use to determine the physical shape is less well reported.

Most published reports emphasise the speed at which E.M. surveys can be carried out. The lack of depth control is often pointed out in connection with the EM31 instrument.

The Self Potential method has been used to detect leachate movements. Stierman (1984) found some success when the method was applied to a landfill site in Stringfellow, California. It appears that seepage potentials are measured; these have been more widely used in relation to seepage through earthdams and reservoirs (Ogilvy, Ayed and Bogolovsky 1969, Bogolovsky and Ogilvy 1970, Cooper and Koesler 1984 and Butler 1984). The principle can be applied to seepage from landfill sites.

## PART II

### AN EVALUATION OF GEOPHYSICAL METHODS AT A LANDFILL SITE SITUATED IN A FORMER SAND AND GRAVEL QUARRY

#### 1.0 THE SITE

The site is in Panshanger Park, near Cole Green, Hertfordshire, Grid Reference T.L. 279124, see (Figs. 1.1 and 1.2 and photograph Plates 1 to 3 in the Appendices). The one inch to one mile geological map, sheet 239, Hertford, shows the succession to be Pleistocene Glacial Sand and Gravel overlying Upper Chalk with Boulder Clay (Till) outcropping at the surface to the south of the site. Gibbard (1977), includes a brief description of the (former) exposure at a Panshanger Quarry which indicates the succession to comprise; sand and gravel overlying till, overlying a second sand and gravel overlying chalk. All strata are of Anglian stage. He correlates the upper sand and gravel with the Smug Oak Gravel which is found more extensively to the south west. He describes it as a cross-stratified gravel with cross-stratified sand lenses. At Moor Mill, to the south of St. Albans, it is 5.2m thick. Panshanger Quarry is near its eastern-most occurrence and hence is likely to be less than 5m thick.

Gibbard (op. cit.) correlates the till with the Eastend Green Till which is a blue grey clay "with abundant chalk, flints and pebbles". At Waterhall Farm, in the Lea Valley

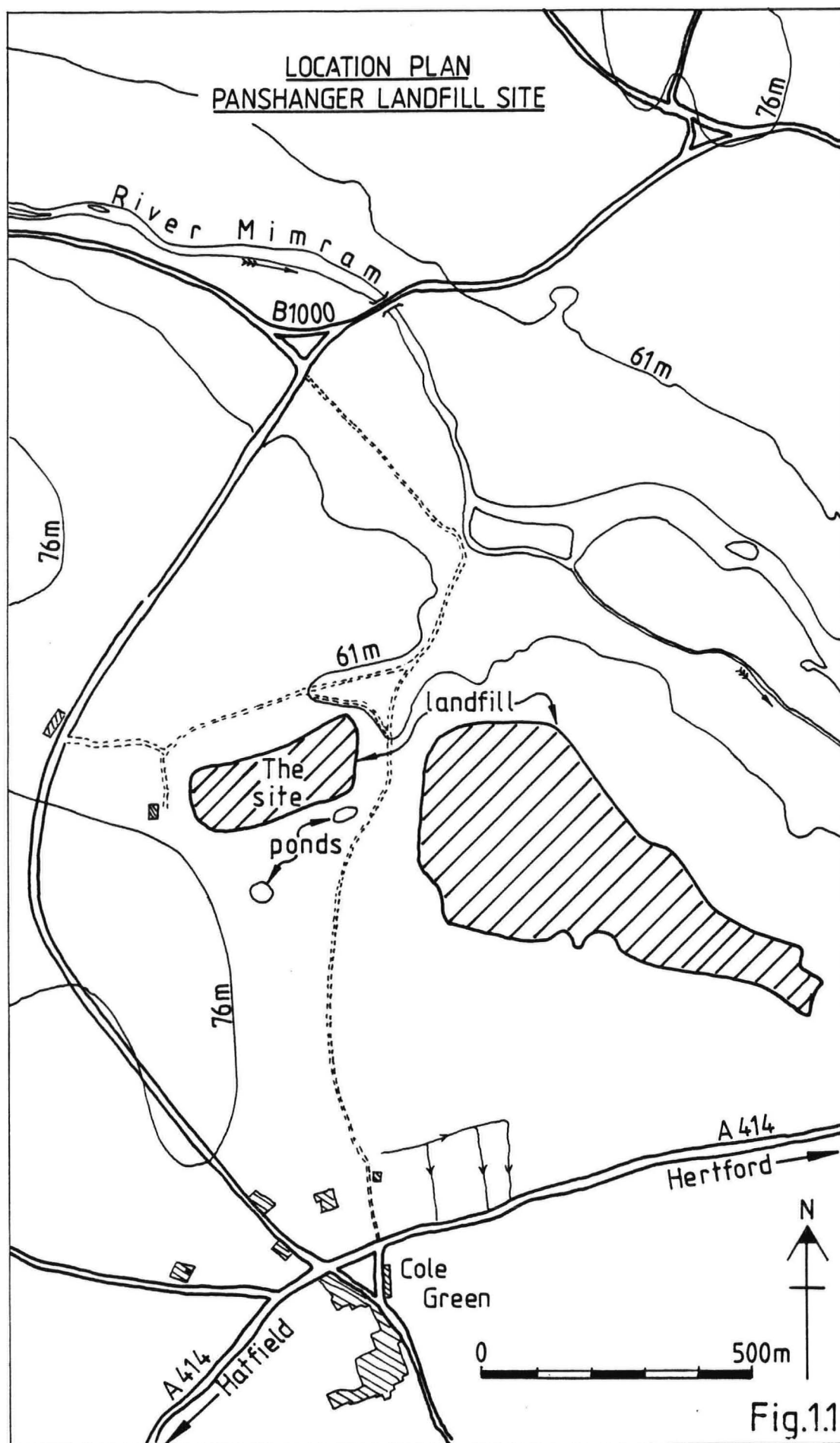


Fig.1.1

PANSHANGER LANDFILL SITE  
Survey grid and location of boreholes

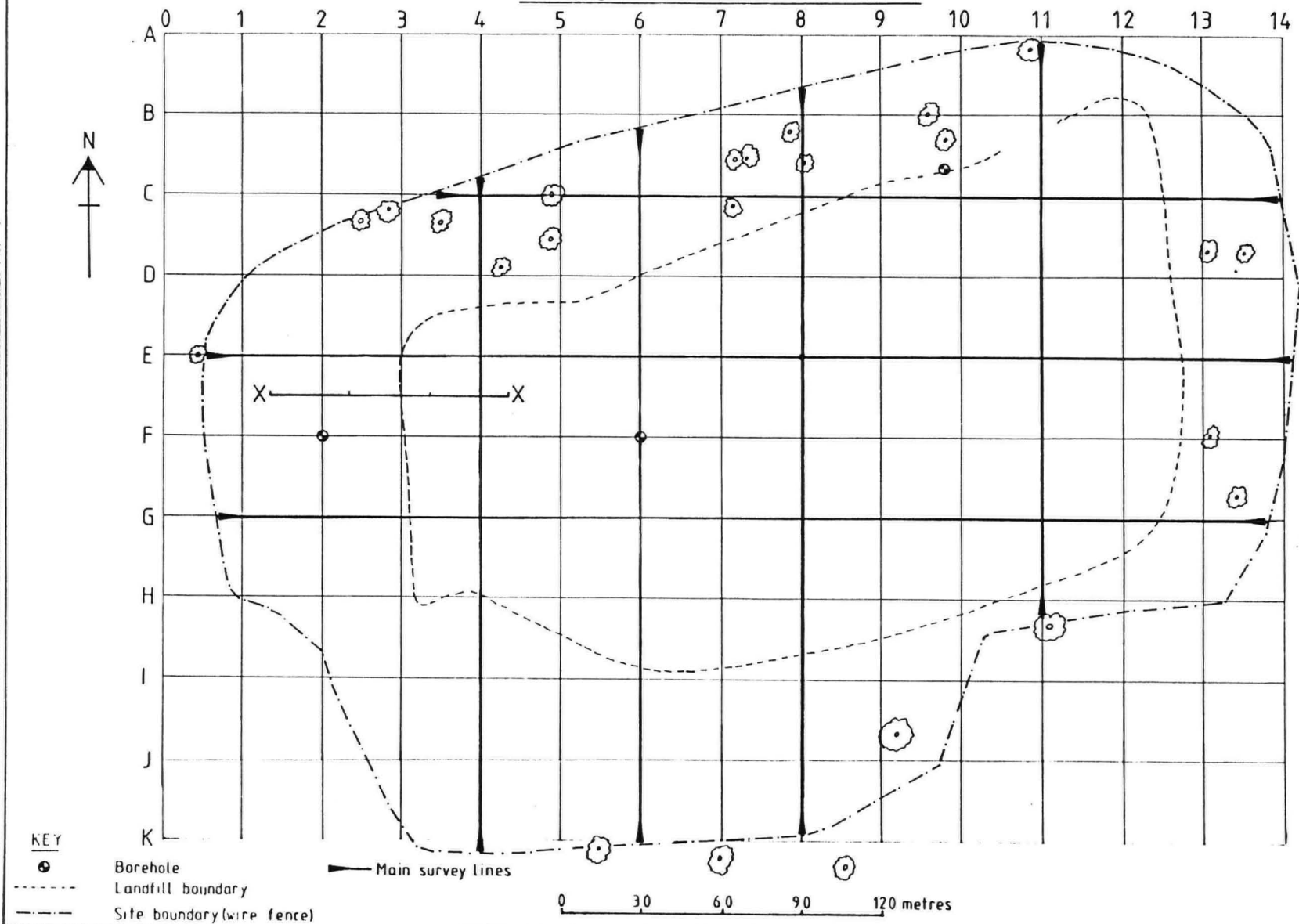


Fig.1.2

to the south of the site, this deposit is 11m thick.

The lower sand and gravel is the Westmill Gravel which he describes as consisting of large gravel lenses sometimes showing internal stratification associated with sand strata. All strata are of Anglian stage. The site is owned by Redland Aggregates Ltd., information from which indicated the following:

Sand and gravel was quarried on the site until the early 1970's. The quarry was then filled with domestic waste and tipping was completed in early 1974. It is understood that the sides of the original quarry would have been excavated at 70° to the horizontal, this being the usual slope of a drag-line excavation in sand and gravel. Prior to back-filling with refuse, the angle was reduced to approximately 45°, firstly by bulldozing reject gravel against the toe of the slope and then by sealing the slope with glacial clay.

The waste was deposited in layers 1.8-2.0m thick, compacted with a steel-wheeled roller and each layer blinded with a layer of reject gravel or "hoggin" (sand and gravel with a clay matrix) approximately 0.15m thick. The source of this information is verbal only, exact angles and thicknesses were not recorded. Access roads were maintained through the tip as tipping progressed, which were made of a "hoggin" type of material. The completed landfill was said to be capped with a 0.6 to 0.9 metre thick layer of clay. It is now leased to a local farmer who uses it as grazing land.

A 30m interval survey grid was used with North-South and East-West axes. This is shown on Fig. 1.2. Positions can be identified by a grid number and a distance increment (in metres), followed by a grid letter and distance increment (For example, the east end of the line x-x would be identified as 4 + 11m, E + 15m). Two East-West lines and four North-South lines were permanently pegged at 30m intervals, from which the other grid lines could be set off by taping when required. Survey lines C, E and G, in the East-West direction and lines 4, 6, 8, 9 and 11 in the North-South direction were used as the main traverses for most geophysical surveys. In general the East-West traverses are up to 390m long and the North-South traverses are up to 300m long.

Redland Aggregates have supplied a sketch plan showing the approximate location of the landfill boundary and is shown on Fig. 1.1. However, a boundary can be located more accurately from the position of a topographic feature surrounding the tip. This appears as a ditch and/or a change of slope. In dry weather there is also an abrupt change in the nature of vegetation cover at the boundary. It was not clear initially whether this boundary feature was produced by the juxtaposition of the clay cap and host material (which need not be coincident with the host/fill boundary) or whether it represented the true host/fill boundary.

The nature of this boundary was therefore investigated in two places by drilling lines of hand-augered boreholes

across the feature. These proved that the topographic feature coincided with the edge of the tip and also that the thickness of the cap was on average 0.5m, rather than the 0.6m to 0.9m stated by the aggregate company. It was also apparent that the cap comprised a clayey sand and gravel in most areas investigated. Clay was found to be the main constituent of the cap only where a large body of standing water formed during winter.

Three deeper boreholes were drilled to give an indication of typical sections through the fill and host material. Their locations are shown on Fig. 1.2. The holes were 200mm diameter, cased and drilled using a cable tool percussion rig ("Shell and Auger"). They were bored in June 1985, which was after the field work had commenced. The boreholes are referred to by their grid reference. The borehole sections are included in the Appendices.

Borehole 6F was drilled to expose a typical section through the fill material. At this position the fill is 4.1 metres thick, comprising 0.9m of clay cap covering 3.2m of refuse (the thickness of the cap is greater than found generally elsewhere). The fill rests on a stiff brown-grey clay with small to medium, rounded chalk gravel typical of the "Boulder Clay" which is shown on the one inch geological map outcropping to the south. It therefore appears that only the upper gravel deposit (the Smug Oak Gravel) has been quarried at this site.



The clay cap has been divided into three 0.3m thick layers on the log. The top two layers are similar except that the lower contains more evidence of artifacts (bricks, clinker and timber) and at the time of drilling, the top layer was more stiff than the underlying layer. The lowest layer in the clay cap contained appreciably more organic material; its moisture content was correspondingly higher (68% compared with 20% for the material overlying it). The samples from the refuse comprised approximately 50% paper, cardboard and wood, 25% glass and plastic sheet and 25% fines, which was largely a black cohesive matrix. Paper and cardboard were not decomposed. It was possible, for example, to read discarded Christmas cards. There was an accumulation of free water at the base of this material 0.1m deep.

The refuse was difficult to drill through using the percussion method. The driller had difficulty in making headway as the cutter tended to bounce. The volume of sample retrieved was less than expected for the depth drilled. It is most likely, therefore, that the samples obtained formed part of a plug which was compressed and driven downward to the clay base. The description given on the log may not be typical of the fill, but it is clear that the fill is compressible.

Standard Penetration tests were attempted in the fill. A value of  $N = 11$  was obtained at 1.0 to 1.45m at the top of the fill. This value is not as low as would be expected from the material recovered. It is equivalent, for

example, to a loose to medium-dense state of compaction in granular materials (B.S. 5930: 1981). The blow count was probably affected by absorption of energy in the fill, thus necessitating a greater number of blows to produce the standard penetration.

Borehole 2F was drilled 30 metres to the west of the filled area through natural ground. In summary the borehole revealed 1.5m of medium-dense sand and gravel, with a transition through sand and clay at its base to a stiff brown-grey clay with small rounded chalk gravel, similar to the material at the base of the fill in B.H. 6F. There was no water table in the sand and gravel.

A third borehole was drilled at 9+24m, B+19.5m at a position near the north east corner of the fill boundary, where anomalous readings had been obtained from some of the electrical geophysical methods. The borehole revealed fill to 1.8m, comprising a 0.5m thick clay cap and a 1.3m thickness of loose refuse, similar to that found in B.H. 6F. This overlaid a dry medium-dense sand and gravel which appeared to be natural. There was no indication of metal in this hole, or of ironcemented sand and gravel.

In summary, the form of the fill material and its relationship with the host material is outlined below using documented information and boreholes.

A simplified section has been compiled across the west boundary using information from boreholes 2F and 6F and that

supplied by the aggregate company (see Fig. 1.4). The full thickness of the fill is not shown on this section, the height of the landfill increases towards BH 6F, where the total depth to "bedrock" was 4.1m. The interface between the waste material and the sand and gravel "batter" is shown as 45° following the advice received from the aggregate company. It is suggested that this interface is to be regarded as the fill/host interface. Although obviously the batter is man-made fill, it is more akin to the host material than the waste material.

There are indications that the model portrayed in Fig. 1.4 is not applicable to the north and south boundaries of the landfill. Fig. 1.5 shows a suggested section through the site on a north south line, based primarily from the geological information available. The section shows the original aggregate deposit to be wedge-shaped with the feather edge to the south.

This form is suggested because there is till shown outcropping at the surface to the south of the site on the geological maps; this is confirmed by field evidence of two ponds to the south of the site, one adjacent to the south east corner and one approximately 50m to the south. According to Gibbard (op. cit.) there is only one till horizon, the Eastend Green Till, therefore the outcrop and the till at the base of the fill are the same. The overlying sand and gravel, the Smug Oak Gravel, is therefore missing to the south of the site, and immediately to the south of the landfill its thickness would be thinner than

## Topographic Sections (vertical exaggeration $\times 2$ )

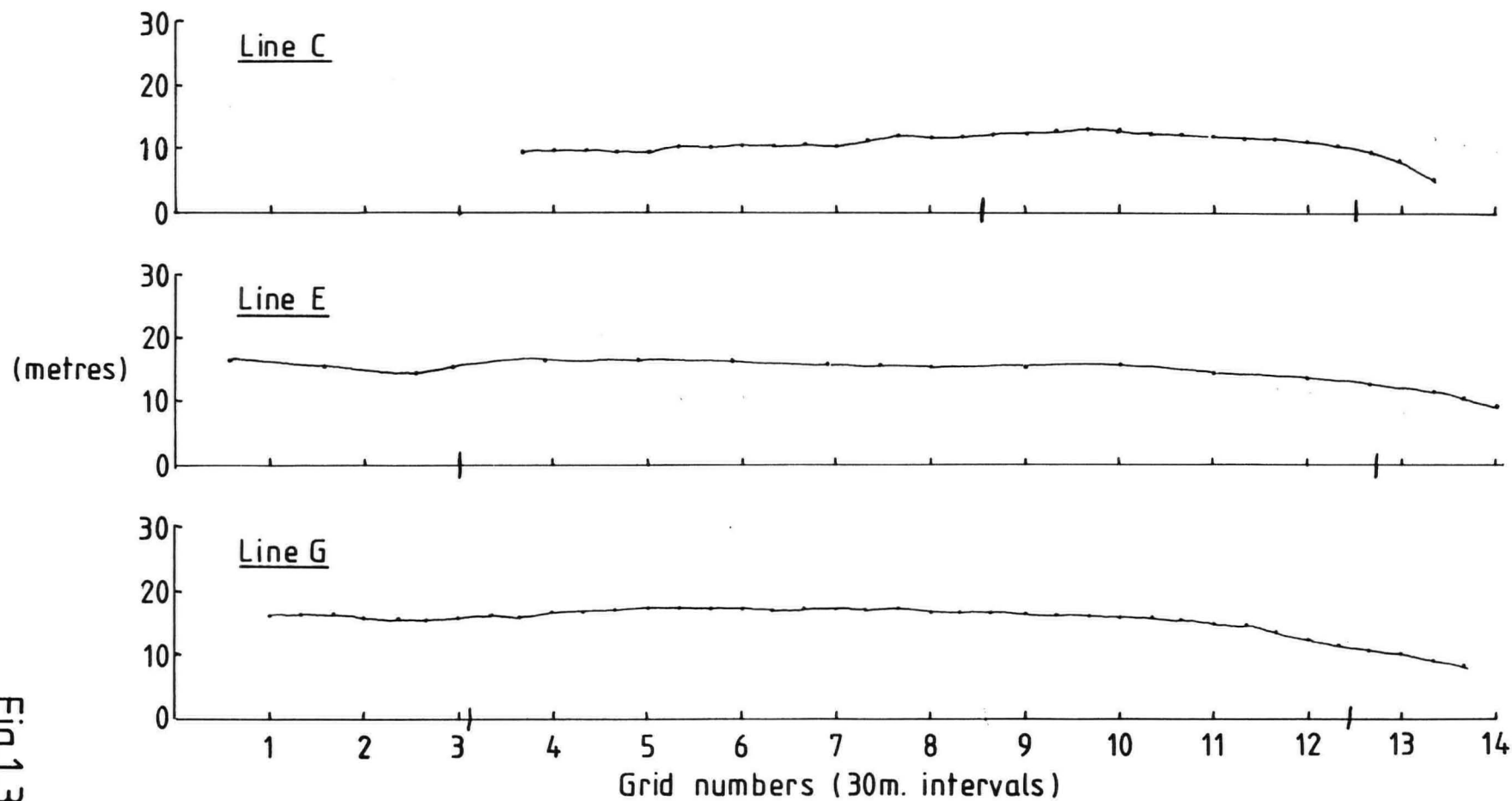


Fig.1.3a

## Topographic Sections (vertical exaggeration $\times 2$ )

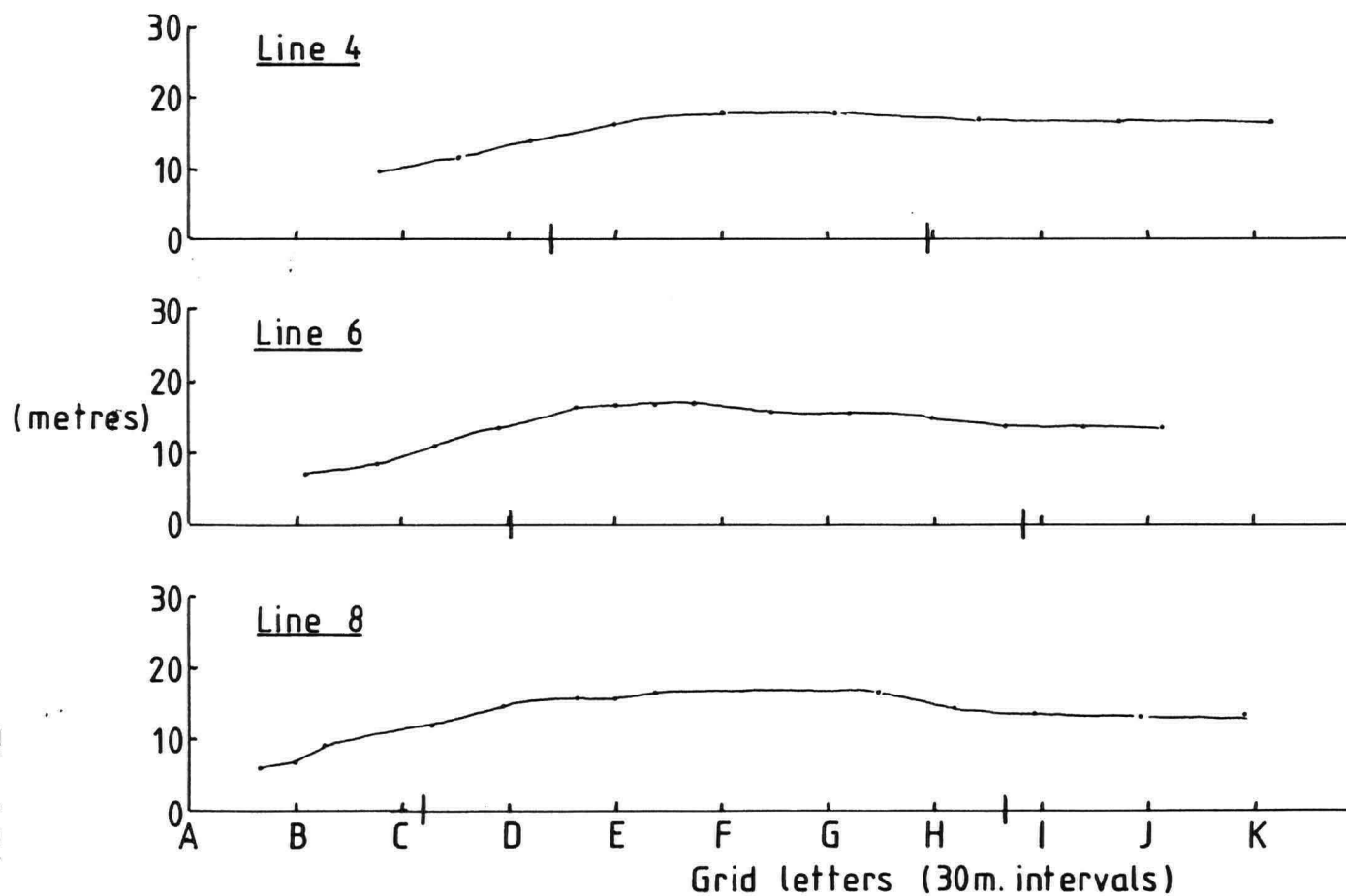


Fig.1.3b

## Topographic Sections (vertical exaggeration $\times 2$ )

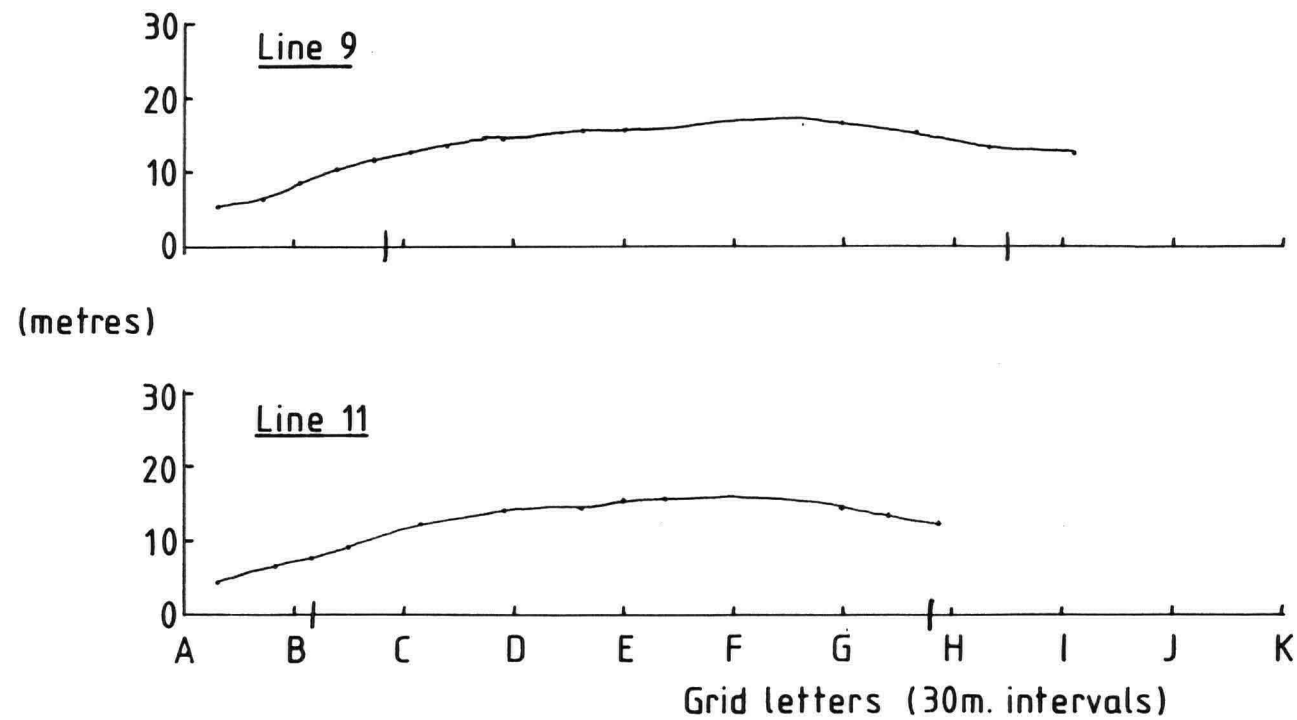


Fig.1.3c

# Simplified section - Line E, west boundary

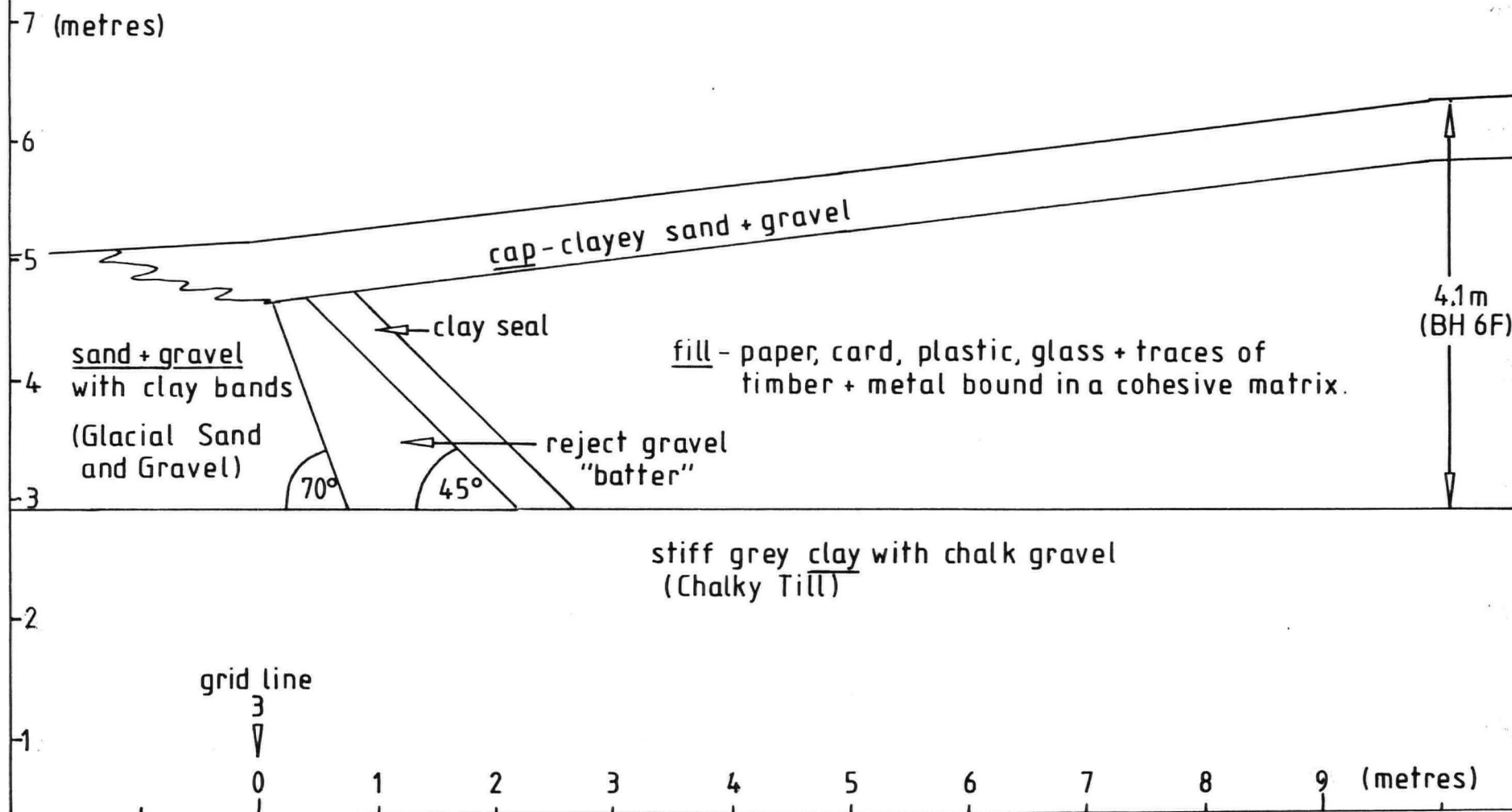
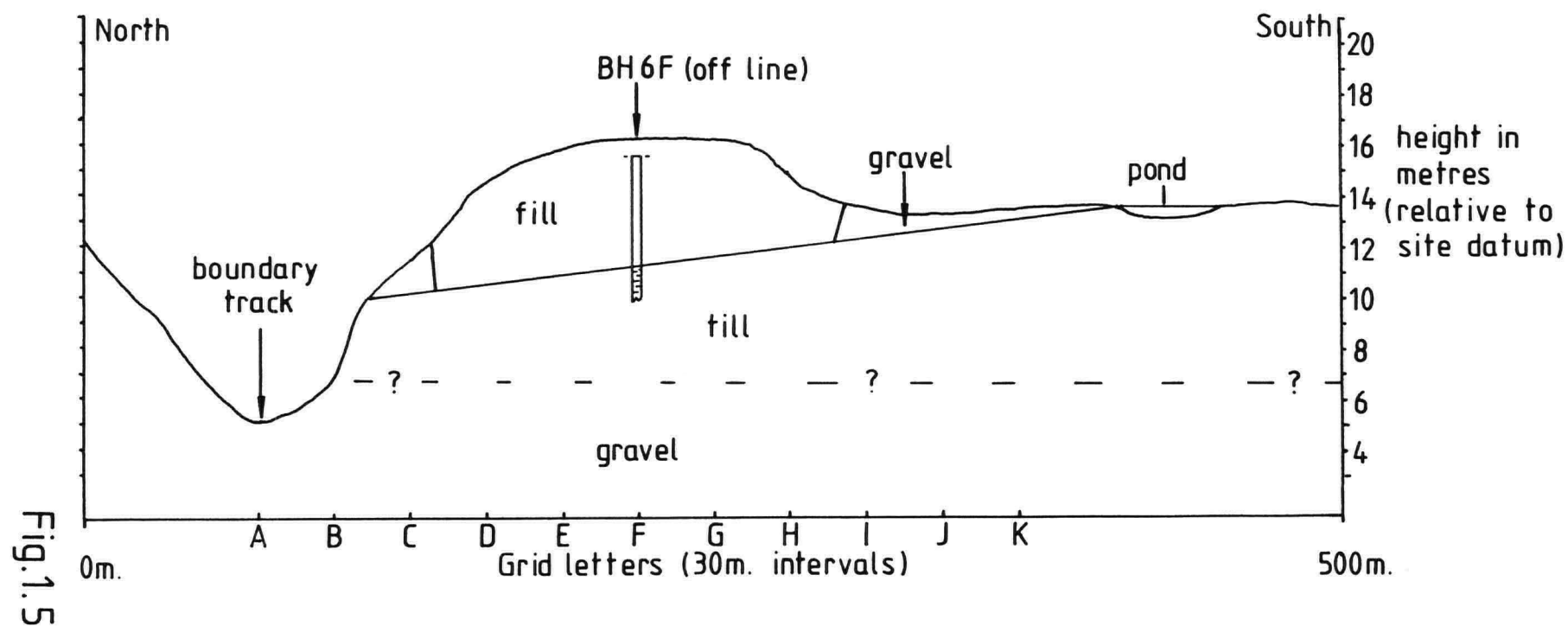


Fig.1.4

North-South section through middle of site  
 ground levels taken from line 8.  
 vertical exaggeration  $\times 10$ .





found in BH2F.

The ground level on the filled area is up to 2.5m higher than the surrounding land at present. The maximum gradient between the fill and host material of 9% ( $5^\circ$ ) occurs on the west boundary. The least gradient of 3% ( $1.5^\circ$ ) occurs on the southern boundary (see the photograph plates in the Appendices). The west boundary is therefore the most distinct, comprising a relatively abrupt change in ground level, whereas the southern boundary is the least distinct.

The ground level on the filled area is generally horizontal. The ground level surrounding the filled area is also horizontal beyond the western and southern boundaries. The ground level continues to fall away from the filled area beyond the northern and eastern boundaries. The maximum height difference on the site as a whole occurs on the northern side, where there is a drop of 10m from the top of the fill to the base of a small valley forming the northern site boundary. The gradient of this slope is 13% ( $7^\circ$ ), which is the steepest on the site. Topographic profiles are shown on Fig. 1.3.

The present study will compare the ability of some surface geophysical methods to detect the position of the host/fill boundary and to determine the depth of the fill. Quantitative or qualitative means of determining the dip of the interface will also be examined. The relevance of these two factors has been outlined previously in Part I, 4.

There has been very little research into the application of geophysical methods to this problem. The obvious difficulty arises from the extreme variability of typical fill materials and their tendency to contain metal. This results in erratic responses from most geophysical measurements, particularly electrical methods, and prevents the selection of interpretation models which are based on simple geometric shapes and layer configurations. In summary, attempts are made to determine whether geophysical responses can be elicited which are more than merely the difference between noisy signal on the fill and a smooth signal off the fill.

The methods used are seismic refraction, resistivity traversing and sounding, electromagnetic induction traversing and sounding, self potential traversing, magnetometer traversing and ground radar traversing.

The seismic refraction method has traditionally been used for shallow investigations in preference to seismic reflection because it is difficult to measure the very small time intervals which is a requirement of shallow seismic reflection surveying. However, there have been some recent reports of the successful use of shallow seismic reflection surveys using shear waves (for example Ohtomo et al, 1984, and Milkereit, Stumpel and Rabbel, 1985), and by improving the source (McCann et al, 1985).

The depth which is of interest in this investigation (about 4m) is very shallow in comparison to the depths referred to by the authors quoted above. A trial reflection survey proved unsuccessful on this site and was not pursued further.

The small amount of published material illustrating the use of seismic survey methods in the investigation of landfill refers to seismic refraction methods. Knight et al (1978) used the method on a waste disposal site near Sydney, Australia, to determine the depth of fill and bedrock. The fill comprised abundant glass, metal and plastic with traces of paper, cardboard and wood. There was also a "brown viscous sludge" which occurred below the water table in the fill at 4m below ground level. The total thickness of fill

was 6.5m. The underlying material was sand, which contained a second water table, and which overlaid shale at 19m below ground level.

Knight et al (op. cit.) carried out two sets of refraction surveys each with multiple reversed shots using 0.4 kg of gelnite in shallow holes. A close spaced "weathering spread" with geophone separation of 3m showed the fill velocity to be 450 m/s, which overlaid a material with a velocity of 1900 m/s.

They carried out a second set of surveys using a geophone separation of 10m. This identified an upper 450 m/s layer, a lower 2800 m/s layer (interpreted as the shale bedrock), but did not clearly show the intermediate 1900 m/s layer.

They concluded that the seismic record was of fair to poor quality. They attributed the poor results to attenuation of the energy in the upper layer which left only the low frequencies, which were difficult to "pick". They found that increasing the shot size made little difference to the received waveform.

Nunn 1979, used seismic refraction to determine the depth of fill on a landfill site at Brownhills in the English Midlands. The fill comprised colliery spoil and domestic fill contained in a depression in the Etruria Marl (Upper Carboniferous) which is a hard calcareous clay and mudstone. The fill rests directly on a variable thickness of glacial drift comprising clays and sands and gravels. The fill

thickness was 5.5m with a water table at 4.5m. The depth to bedrock was 12m.

Reversed refraction profiles were surveyed using a geophone spacing of 6m and explosive charges of 0.23 kg to 1.1 kg. Three layers were identified; an upper layer with a velocity of 500 m/s, an intermediate layer with velocity of 1300 m/s and a lower layer of 2200 m/s. The upper and intermediate layers were correlated in boreholes with dry and wet fill respectively, the lower layer was identified as the bedrock. The method therefore failed to distinguish the fill/drift interface. They proposed that the drift would have a velocity of about 1600 m/s and was present as a "hidden layer".

The fill at Pansanger appears to be more like that reported in the study by Knight et al, than that reported by Nunn.

### 3.2 Method and Equipment

The equipment used was Geometrics-Nimbus Models ES-1200 and 1210 twelve channel signal enhancement seismographs. The shot source was a 14lb hammer striking a steel plate seated at the underside of the topsoil. The spreads were located on Lines 6 and F (see Fig. 1.2).

Refraction profiles were run with reversed shots and with an additional shot in the centre of the spread. The geophone spacing varied from 1m to 6m. The shot was in line with the geophone spread. The lengths of the individual spreads were

set to ensure that the refracted wave from the base of the fill should have been received. The critical distance was determined using the relationship between velocities and depths shown on Fig. 3.1 (from Redpath 1973). This approximates to the often quoted rule of thumb which states that the spread length should be ten times the depth of interest.

It was anticipated that the main difficulty of the seismic refraction method would arise from the likely existence of a velocity reversal on the fill area. Borehole 6F had shown a clay cap overlying a loose and spongy fill material. Some time was spent checking the results of the survey in the field, particularly on the fill to ensure that the first arrivals had not been missed. Full use was made of the signal enhancement capability of the instruments and also of the filters in the 1210 model.

The shallow depths which are of interest on this site require accurate "picking" of arrival times. This requires a well defined waveform, which in turn depends initially on a good coupling of the shot source with the ground. Attention was paid to ensuring that turf and topsoil were removed to provide a flat surface on which to place the plate. Thereafter, the waveforms were manipulated by using the amplitude and gain controls of the seismographs.

The effect of topography should be considered in the interpretation. The difference in elevation is 1.5m across the boundary on Line E (adjacent to Refraction Line F),

which is a significant proportion of the depth which is of interest. The usual method required the arrival times to be corrected to a common horizontal datum. This correction was not applied here because, as will be discussed, the quality of the refraction record was insufficient to allow an interpretation across the boundary, which is the position where elevation changes.

Relationship between the Critical Distance  
and the depth and velocity ratios



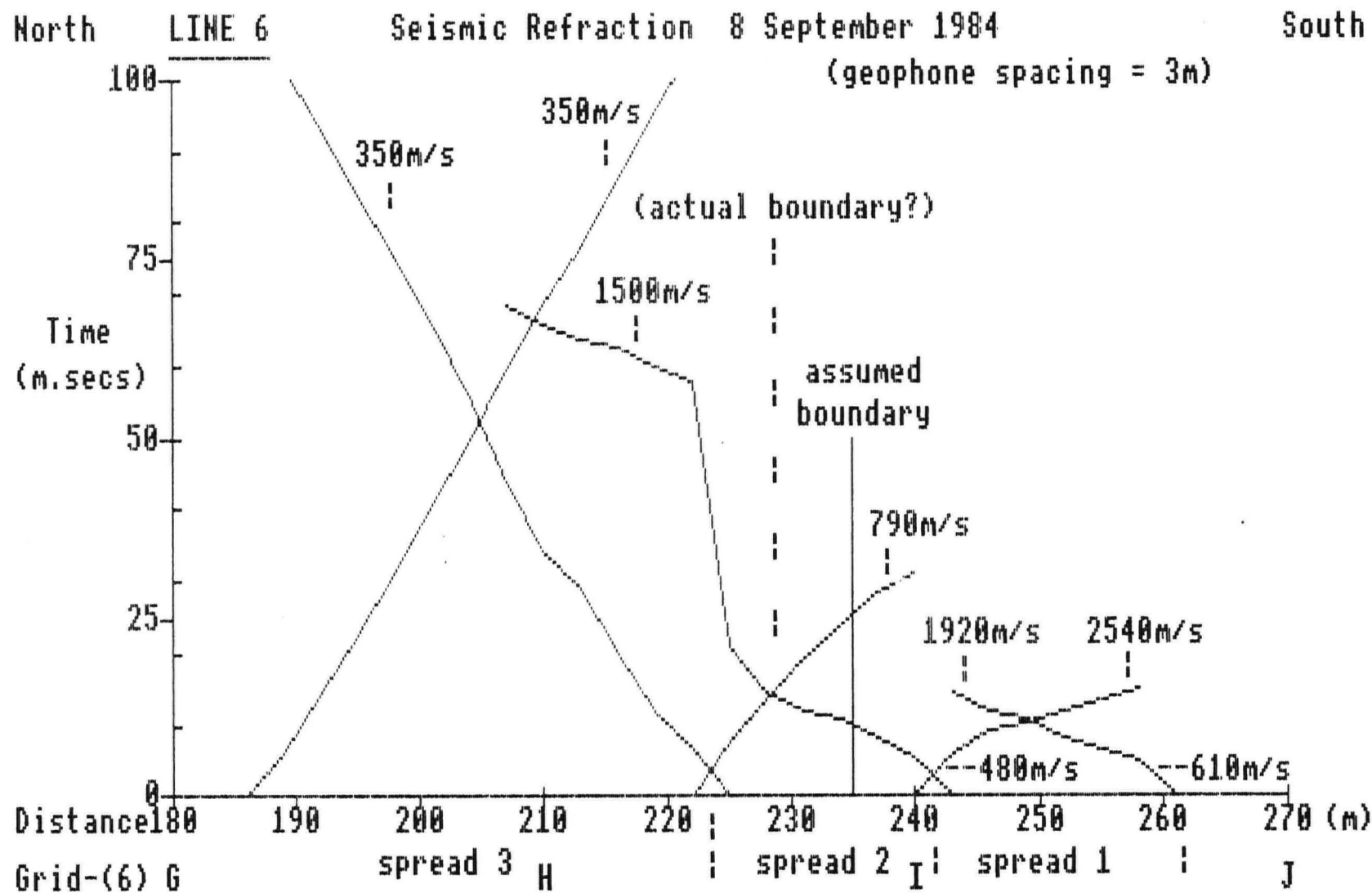


Fig.3.2

discontinuity on the time-distance curve would be displaced away from the shot point, relative to the actual ground discontinuity. The amount of the displacement would be of the order of  $h \times \tan \theta_c$ , where  $h$  = the depth to the refractor and  $\theta_c$  = the Critical Angle. Assuming that the depth to the refractor is about 1m (from the borehole information), the displacement would be of this order or less.

The 1500m/s velocity shown on Fig 3.2 beyond the discontinuity is not so clear on the refraction record as the earlier arrivals, but it appears as a consistent velocity recorded by the furthest 6 geophones.

There is no corresponding change in velocity on the branch of the time-distance curve shot southwards across the discontinuity. An apparent increase in velocity would have been expected and manifested as a flattening of the curve at a point offset southwards from the true discontinuity. (Another spread shot southwards across the boundary, omitted from Fig 3.2 for clarity, also failed to show such a feature).

To the north of the boundary, there are only direct arrivals with a velocity of 350 m/s. It is unlikely that the wave forms which were picked to produce the time distance graph of spread 3, are anything other than the P wave direct arrivals. The wave form is similar to that at the first geophone on spread 1, which can safely be assumed to be the P wave direct arrival. Consequently this must be the

velocity of the clay cap.

The simple derivation of depth and velocities south of the boundary outlined above fits an interpretation of dry sand and gravel over clay. (Typical velocity ranges of these two materials are given by Redpath (1973) as 468-915 m/s and 915-2750 m/s respectively). There is no borehole at the position of this spread, but borehole 2F, which is also off the tip shows in its simplest interpretation 1.5m of sand over clay, which is in general agreement with the interpretation of this seismic record.

The time distance graph north of the boundary shows an unusually low velocity (350 m/s) typical of weathered surface material of moist loamy or silty topsoil (Redpath op. cit.). The survey was carried out at the end of a dry summer and so it appears likely that the low velocity is due to the poor compaction of the clay cap and consequent high porosity which is the parameter which most affects the velocity of the P waves.

### 3.3.2 Line F

A series of refraction spreads were shot on Line F across the boundary (Fig. 3.4). Both the 1200 and 1210 seismographs were used. The latter had the advantage of a C.R.T. display which allowed easier manipulation of the recorded waveform, thus making it possible to check that all waveforms had been registered. The 1210 machine had a disadvantage over the 1200 machine arising from the method

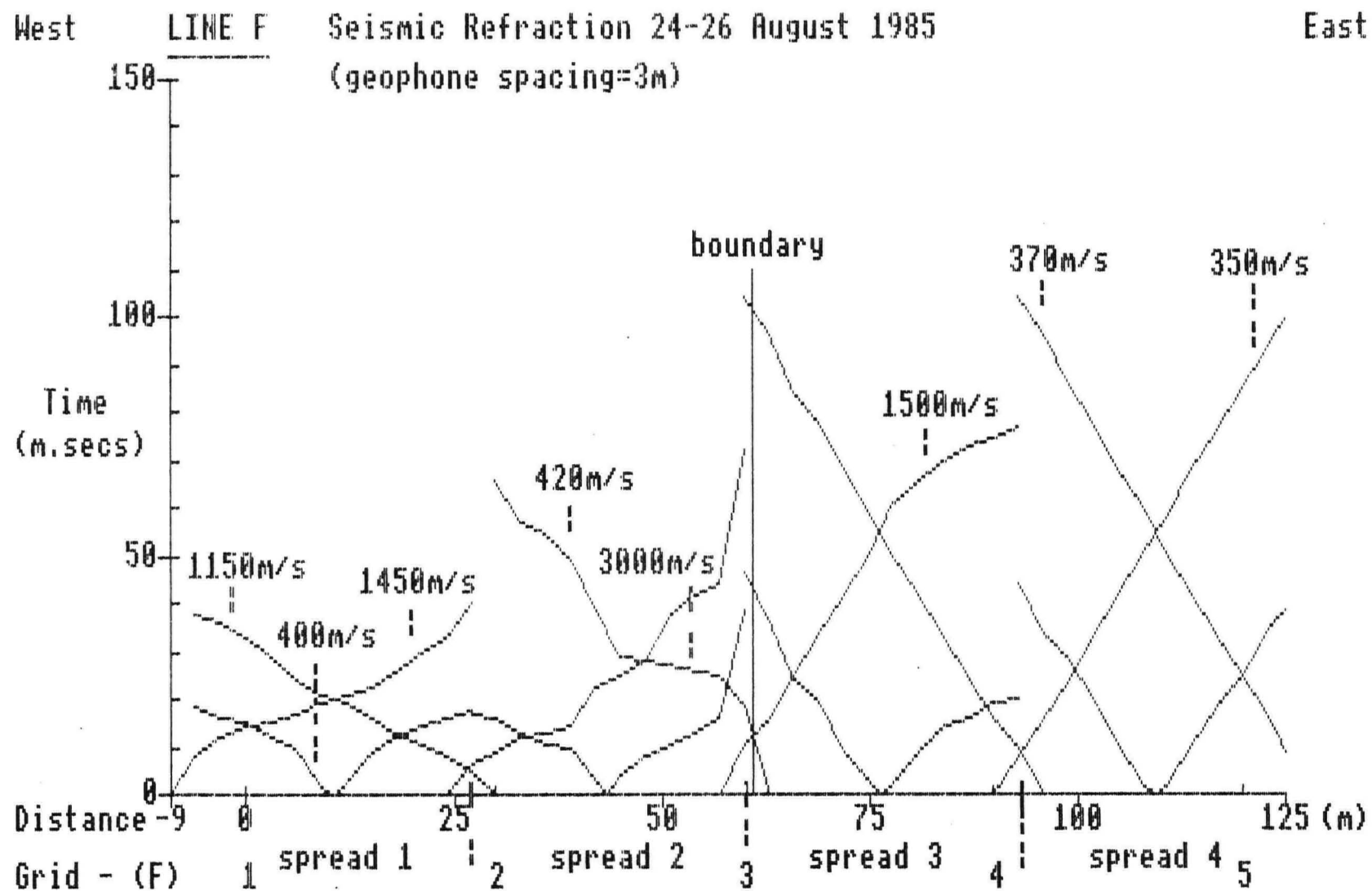


Fig. 3.3a

# Seismic Refraction Line F (part)

24 - 26 August 1985

West

Plot of depth to second layer, obtained from Delay Time Method.

East

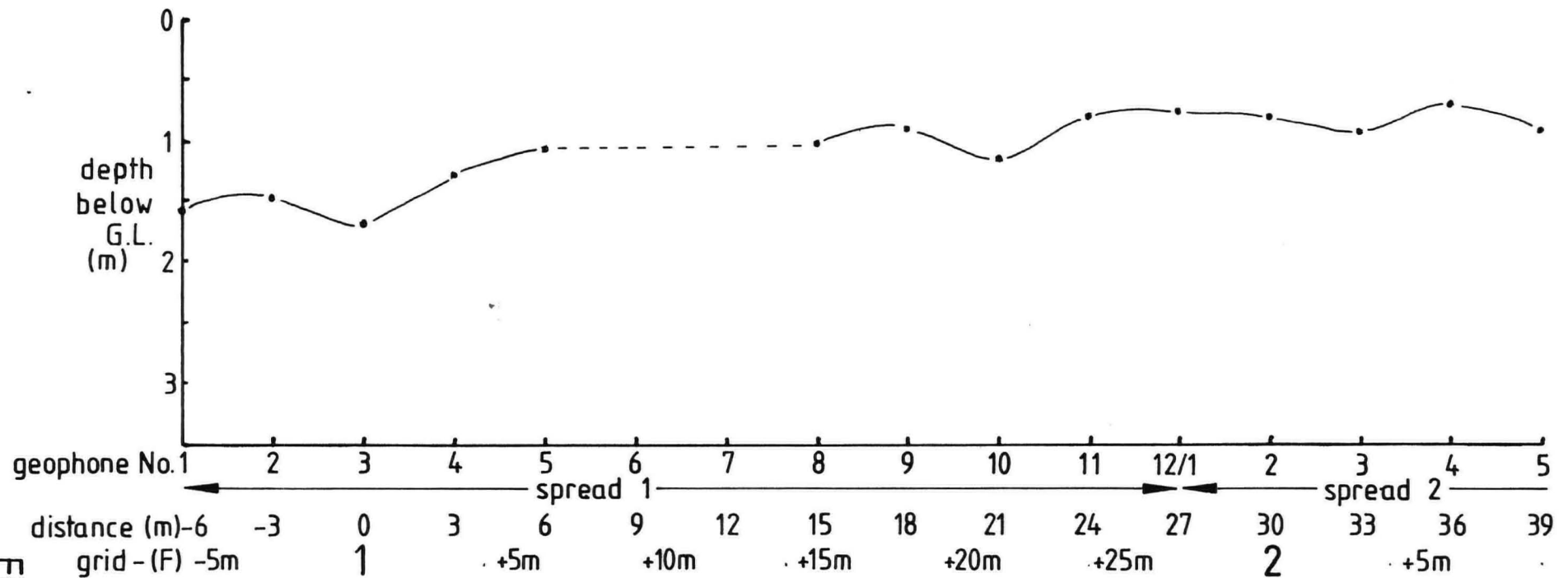


Fig. 3.3b

of printing. The former had a dot matrix type printer which was less able to display small waveforms than the latter's U.V. printer.

The time distance graphs off the tip have been interpreted using the method of delay times, first proposed by Gardner (1939). In most cases, on the series of spreads off the tip, the first part of the time-distance curve included a geophone which enables the slope and hence velocity of the first layer arrivals, to be defined. The first layer thickness varies from 1.6m to 0.9m, which is in general agreement with the thickness of sand and gravel in B.H.2F. The velocities of the layers  $V_1$  and  $V_2$  are in the region of 400 m/s and 1400 m/s respectively. These values are again within those previously quoted for dry sand and gravel, and clay.

The time distance curves show the same features at the boundary as exhibited on Line 6. There is an apparent decrease in velocity at the position of the boundary and, on the fill side of the boundary, direct arrivals only are recorded. The velocity of the clay cap is again in the region of 350 m/s.

On spread 3 (shot west - geophones east) there is a suggestion of a second layer with a velocity of 1500 m/s. This waveform was difficult to pick on the refraction record, but credibility is gained from the occurrence of an identical velocity on Line 6 noted previously. This may represent the velocity of the clay at the base of the tip. The curve produced by shooting from the tip across the boundary, on

Line F, shows an apparent increase in velocity which is the characteristic feature produced by a sub-vertical boundary with the shot on the lower velocity material (Griffiths and King, 1981).

Several attempts were made to propagate energy through the fill, which if successful, would have produced a second branch on the time distance curve arising from the refracted wave along the clay base (but which would have indicated a depth which was false if a velocity inversion existed). Fig. 3.4 shows some of the curves produced on a total spread length of 36m. The geophone spacing over the first 6m was 1m, and beyond that it was 6m. There is no indication of an early (shallow) velocity change. The velocity remains at about 350 m/s for the full spread length, thus indicating that the recorded wave is the direct arrival.

Further surveys were run with the object of trying to pick out any refracted low frequency attenuated waves, preceding the direct arrivals. If energy was being absorbed by the fill, it would affect the high frequencies leaving low amplitude, low frequency waves (Knight et al op. cit.). This exercise was not successful. The background noise (which was not severe) proved too great to enable any weak refracted wave to be detected.

The seismic refraction method was found to be the most time consuming of the methods tried. This was a consequence of the time taken to set up the equipment initially and of the

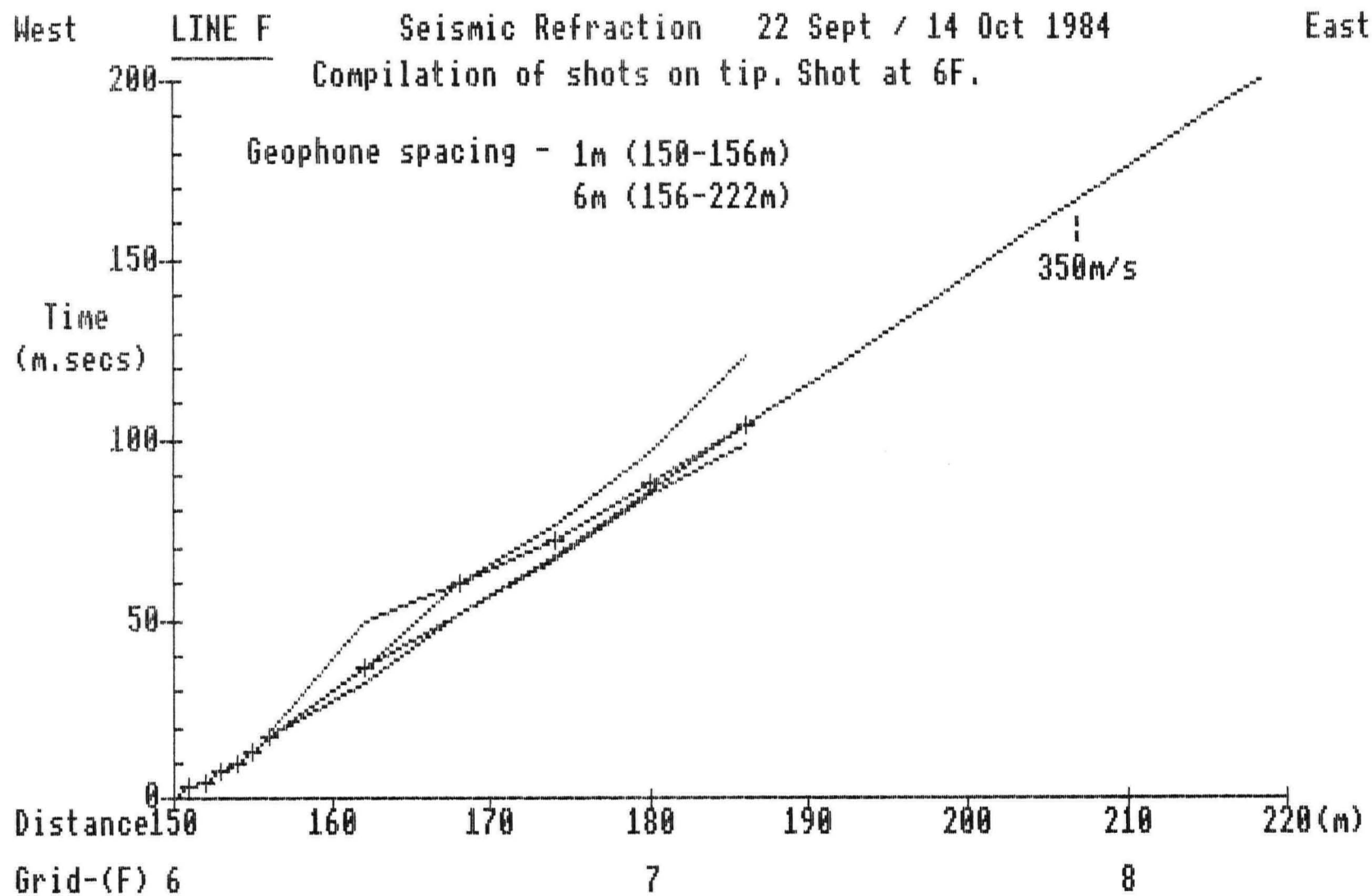


Fig. 3.4



time required to condition the first arrivals to useable waveforms. Owing to the particular difficulties with wave propagation on this site, it was sometimes necessary to spend half a day on one geophone spread.

### 3.4 Conclusions

The refraction method is not capable of determining the depth of fill on this site using a surface shot source comprising a 14 pound hammer. The problem arises not only from a possible velocity inversion, which was expected, but from an inability to propagate enough energy through the fill material. This was a consequence of the nature of the fill which was evidently far from being an elastic medium, required for seismic wave propagation.

This difficulty was also experienced to a lesser extent by Knight et al (op. cit.) using gelignite buried at a depth of 0.75m as a shot source.

It can be inferred that, for the site at Panshanger, burial of the shot source, and an increase in shot energy, would have succeeded in propagating some energy through the fill. There have been some instances of more successful results using a "Buffalo Gun" as a shot source (J. Smith, personal communication). This device fires shot gun cartridges into the ground. It is also possible that, if the fill velocity reported by Knight et al (op. cit.), which was 450 m/s, is typical of the Panshanger fill, there may not have been a velocity inversion, in which case, the poor result is due entirely to energy dissipation in the fill. The difficulties experienced during the drilling of boreholes in the fill illustrate the extent to which the fill absorbs the percussive energy applied.

If it had been possible to propagate energy through the fill it is unlikely that the waveform received would be sufficiently coherent to enable it to be used to obtain a reliable travel time. The part of refracted wave which had not been absorbed would be relatively low frequency and low amplitude. Accurate "picking" of the travel time would not be possible. This is a serious drawback when dealing with very shallow depths.

The method appears to have been successful in determining the depth of sand and gravel over clay. The survey could have been more successful in this respect if the initial geophone spacing had been reduced. However, the objective was not to determine the depth of overburden; the ability of the technique to achieve this is well known.

The position of the boundary can be estimated from a spread with the shot off the tip and the geophones spread across the anticipated position of the boundary. Both Figs. 3.2 and 3.3, Lines 6 and F, show a distinct break in the time distance curve at the boundary position, but the results suggest that the assumed boundary position on Line 6 is in error and should be placed approximately 6m further north.

Seismic refraction is generally time consuming. The conditioning of the waveform, to produce a good break, involves considerable trial and error. This was found to be true for this site in particular, which can be regarded as a difficult site for seismic refraction. In view of the time required to obtain results, there is little to recommend

this method as a tool for the detection of fill boundaries  
over other less time consuming methods.

#### 4.0 RESISTIVITY SURVEYING

##### 4.1 A Review of Similar Applications

The ability of constant separation traversing to detect leachate and indicate its relative concentration is well established and examples of previous work are included in the chapter 2. One of the necessary conditions for success is that the variation in lithology should be minimal so that the effects of leachate concentration are not masked (Klefstad et al, 1975). This conclusion had been previously reached by Cartwright and McComas (1968), who also concluded that the depth to the "zone of saturation" (water table) should not vary if the method was to be successful.

The corollary of satisfying these conditions, which is relevant to this study, is that, where there is a high concentration of leachate, in particular within the landfill area, and ground with a low resistivity contrast, it is likely that the effect of the low conductivity of the leachate would mask the lithology and thus inhibit quantitative interpretation of the geomorphology of the original tip.

There is very little published information on the use of constant separation traversing to detect boundaries. Most examples refer to depth probes (soundings).

Cartwright and McComas (op. cit.) attempted an interpretation of Wenner configuration resistivity soundings with only partial success adjacent to a landfill site in Du Page County, Illinois. They attributed the poor results to the masking effects of "mineralized water" (leachate). Nunn (1979) reported a successful interpretation of Wenner resistivity soundings at a landfill site at Walsall in the English West Midlands. Eight soundings each revealed the depth to the water table and to the fill/bedrock interface.

The reason for the difference in success rates is probably due to differences in resistivity contrasts at the two sites. Cartwright and McComas were working on a landfill situated in Pleistocene glacial deposits which are described as "mainly fine silty sand". Typical resistivities quoted were in the range 26 to 30 ohm metres. Nunn was working on a landfill situated in the Coal Measures which had a resistivity of 200 ohm metres. In both cases, the resistivity of the saturated fill and leachate was in the region 2 to 5 ohm metres. It is clear that there was a greater contrast between the fill and host material at the West Midlands site than at the Illinois site.

Knight et al (1978) used Wenner soundings on a landfill site at Lucas Heights near Sydney, Australia, with the object of determining the geological profile through the landfill. They used what they termed "star" soundings, which were the usual duplicated soundings, with the electrode arrays at right angles to each other. They found little difference between the two sets of results and concluded that the

landfill could be treated approximately as a layered geoelectric section. They appear to have used a manually smoothed curve plotted through the point scatter.

Their soundings were taken to a maximum 'a' value of 40m. The interpretation was carried out using the auxiliary point method (Bhattacharya and Patra 1968). It showed a geoelectric section comprising a 500 ohm m layer 0.8m thick over a 16 ohm m layer 19m thick over a 160 ohm m bedrock (shale). The top geoelectric layer was interpreted as "cover material" although it was not distinguished separately on the corresponding borehole log. The borehole showed the thickness of the fill to be 6.5m and this overlaid 12.5m of sand. The resistivity interpretation therefore did not distinguish between wet fill and sand, but the thickness of the second resistivity layer corresponded well with the known depth to bedrock from the borehole. It appears that leachate in the fill and sand below was masking the lithology as reported by others.

The landfill site which is the subject of the present investigation is situated in sand and gravel with a stiff clay base. In terms of resistivity contrast, it is therefore likely to be better than the Du Page County site (Cartwright and McComas), but worse than the Walsall site (Nunn). Because the resistivity contrasts are dependant on the lithology of the host material, and in particular on the ground water conditions, conclusions drawn from the results will be site specific.

## 4.2 The Equipment

The equipment used was an ABEM Terrameter SAS 300. The current is produced in discrete positive and negative pulses similar to a low frequency alternating current. This current pattern is said by the manufacturers to avoid the necessity for non-polarising electrodes and allow deep current penetration. Readings are continuously displayed as a running average of 4, 16 or 64 cycles. Generally 4 cycles were used unless the running average was still showing a variation at the end of the cycle, in which case further readings were obtained.

## 4.3 Resistivity Traversing

### 4.3.1 Method

The site was investigated using Wenner constant electrode separation traverses (profiling), along lines 10 metres apart. Readings were taken at 10 metre intervals so that a 10 metre grid of apparent resistivity values was built up. The survey was conducted at intervals between 18th March and 29th July 1984, during which time the ground surface changed from water-logged to dry and 'hard'. The effect that this had on the apparent resistivity was monitored by taking readings at two base stations, one on the fill and one off (grid positions 8E and 1E respectively).



Trials were performed across part of the fill/host boundary using different values of 'a', the electrode separation. The final electrode separation was chosen on the basis of both performance and operating convenience. The depth of material which contributed to the apparent resistivity was not considered as of prime importance, provided that the apparent resistivity showed an easily recognisable change at the host/fill boundary. The trials showed that an 'a' value of 2 metres produced a noisy signal, with inconsistent results over the fill area. A value of 6 metres produced a smoother profile whilst still providing a contrast of 2:1 between the two materials (see Fig. 4.1). Klefstad et al (1975) found little difference between iso-resistivity maps compiled from traverses made with 'a' values of 4, 6, and 9 metres, but it was subsequently found by Palmquist and Sendleim (1975), working on the same site, that the 6 metre spacing was the theoretical optimum for the target depth (a low resistivity leachate plume).

A 10m electrode spacing provided a practical advantage to the execution of the survey because, as it coincided with the station interval, it was necessary to move only one electrode between readings and then to rearrange the cables. Provided that the cable lengths were sufficient, thus minimising the number of times the Terrameter was moved, the procedure was found to be as quick as traversing with a Schlumberger or dipole-dipole array, in which two electrodes are moved between readings.

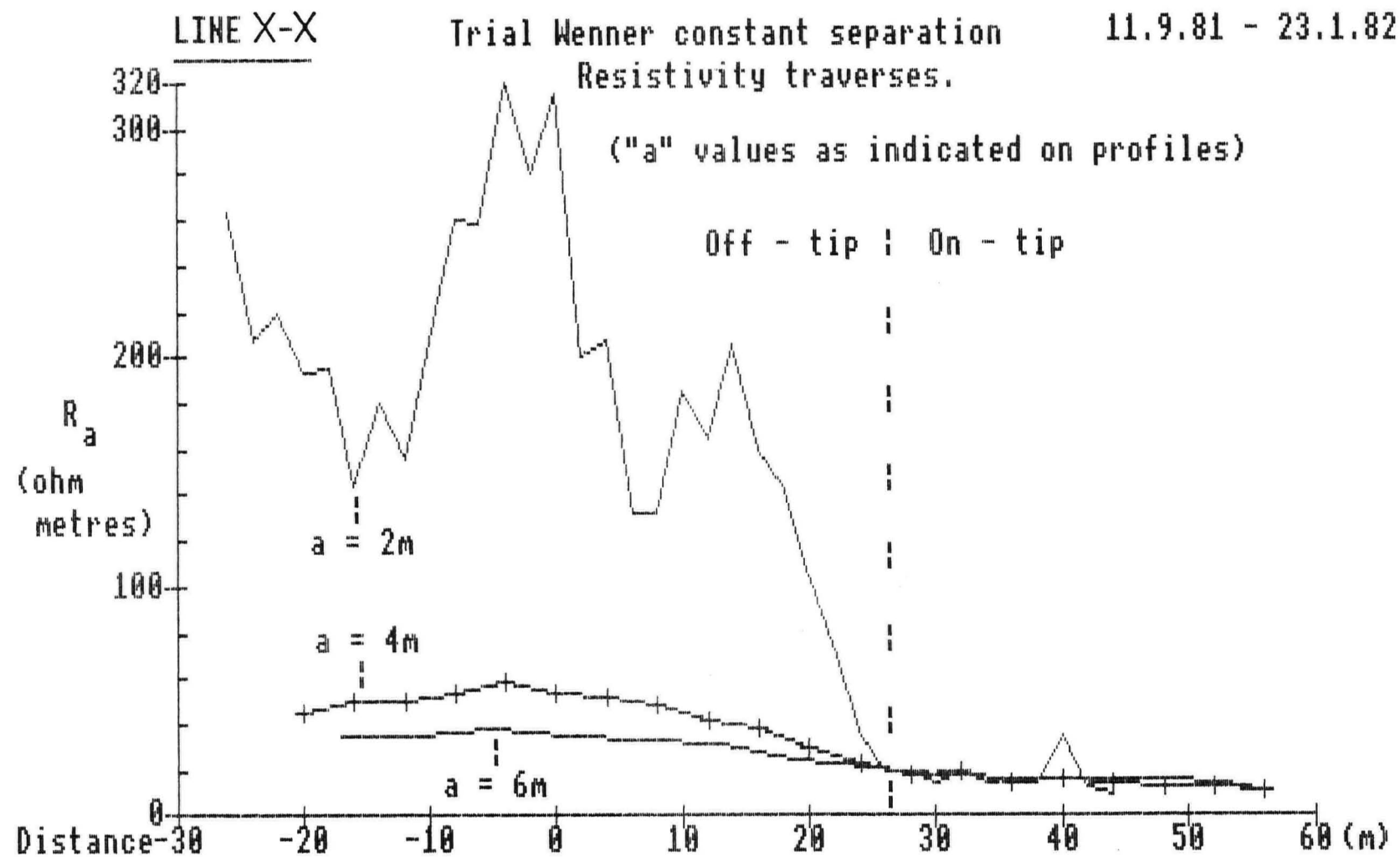


Fig. 4.1

The electrode array was always spread along the east-west grid lines and the array advanced along the same grid lines. There are therefore 28 profiles available from grid Line A+10m in the north, to J+10m in the south. A further 38 profiles in the north-south direction can be compiled from successive traverses from 1+10m in the west to 13+20m in the east, where the electrode array is perpendicular to the survey line. These compiled traverses in the north-south direction comprise individual readings which are separated in time by up to four and a half months; the greatest difference between adjacent readings being between Line D and C+20m, which were surveyed on the 18th March and 15th July respectively. The effects of variation in the ground saturation were therefore considered.

#### 4.3.2 Interpretation Techniques

The orientation of a colinear electrode array relative to a vertical boundary affects the apparent resistivity profile produced over the boundary. Telford et al (1976) present formulae based on image theory from which the response of any electrode configuration, used to traverse across a vertical boundary, can be calculated. It is not assumed that the boundaries of the filled area on the site being investigated are vertical. However, it is expected that profiles in the region of the boundary taken with the electrode array parallel to the traverse line would differ from those compiled in a direction perpendicular to the electrode array.

The electrode array used in this investigation (Wenner) is symmetrical, the current is A.C., and therefore the direction of traversing across the boundary should make no difference to the profile produced. If the electrode array had been one of the non-symmetrical types, which might have been easier to use in the field, the direction of survey would have had to be constant.

The effects of orientation of the electrode array in relation to a boundary can be overcome or controlled by using the square electrode configuration. A short traverse (Line X-X) was surveyed using constant separation traverses in a square array. Broadbent and Habberjam (1971) describe a method of interpreting the dip of an interface using the profile obtained from a square array traverse. They show that the apparent resistivity profile changes uniformly across the interface. The shape of the resistivity profile depends on the resistivity contrast ( $k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$ ) the dip angle ( $\alpha$ ) of the interface, and to a lesser extent, on the orientation of the electrode array relative to the strike.

Broadbent and Habberjam (op. cit) found that the main difficulty in using master curves calculated for various values of  $\alpha$  and  $k$  was that the curves were very similar. They concluded that traversing was well suited for determining the strike of an outcrop and estimating 'k', but not very good at estimating the dip.

They went on to describe their "Abbreviated Mapping System", which utilises a relationship between a quantity which they termed the "half width" and the ratio  $\rho_2 / \rho_1$  to define the dip angle. The half width is illustrated on Fig. 4.2. The position of the outcrop of the interface can be determined by obtaining the distance  $x/a$  from their Fig. No. 5. This is also shown on Fig. 4.2.

The master curves are presented in the paper by Broadbent and Habberjam. Their usefulness is limited because the curves are sub-parallel to the  $\rho_2 / \rho_1$  axis which makes reliable values difficult to obtain.

"Half width" and distance to outcrop

(from Broadbent and Habberjam 1971)

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The master curves are presented in the paper by Broadbent and Habberjam. Their usefulness is limited because the curves are sub-parallel to the  $\rho_2 / \rho_1$  axis which makes reliable values difficult to obtain.

#### 4.3.3 Presentation and Discussion of Results

##### 4.3.3.1 The Results

The variation of apparent resistivity with time over the period of the survey at the two base stations is shown on Fig. 4.3. The maximum difference obtained from the base station on the host material is 1.0 ohm metres. The maximum difference obtained from the fill material station is an increase of 5.8 ohm metres which occurred between the 15th July and 29th July during a period of warm dry weather. Presumably this was caused by drying of the clay cap. The lines surveyed during this period were C + 20m northward to A +10m. These lines were largely on the host material, which was less affected by time dependent changes and so a correction has not been applied to the original values.

During the dry period difficulties were experienced in obtaining consistent readings. These were attributed to poor electrode contact resulting from the dryness of the ground. The difficulties were usually overcome by increasing the voltage applied, driving the electrodes further into the ground or, if neither of these methods worked, obtaining sufficient readings to indicate the average. It was also noted that during windy weather, with dry ground, the readings were erratic. Some workers have applied water to the electrodes in these circumstances, in particular, Knight et al (op. cit.) applied salt water. This was not done in this case because of the difficulty of ensuring a uniform treatment to all electrodes, which,



Variation of Resistivity with time, 22nd April - 29th July 1984.

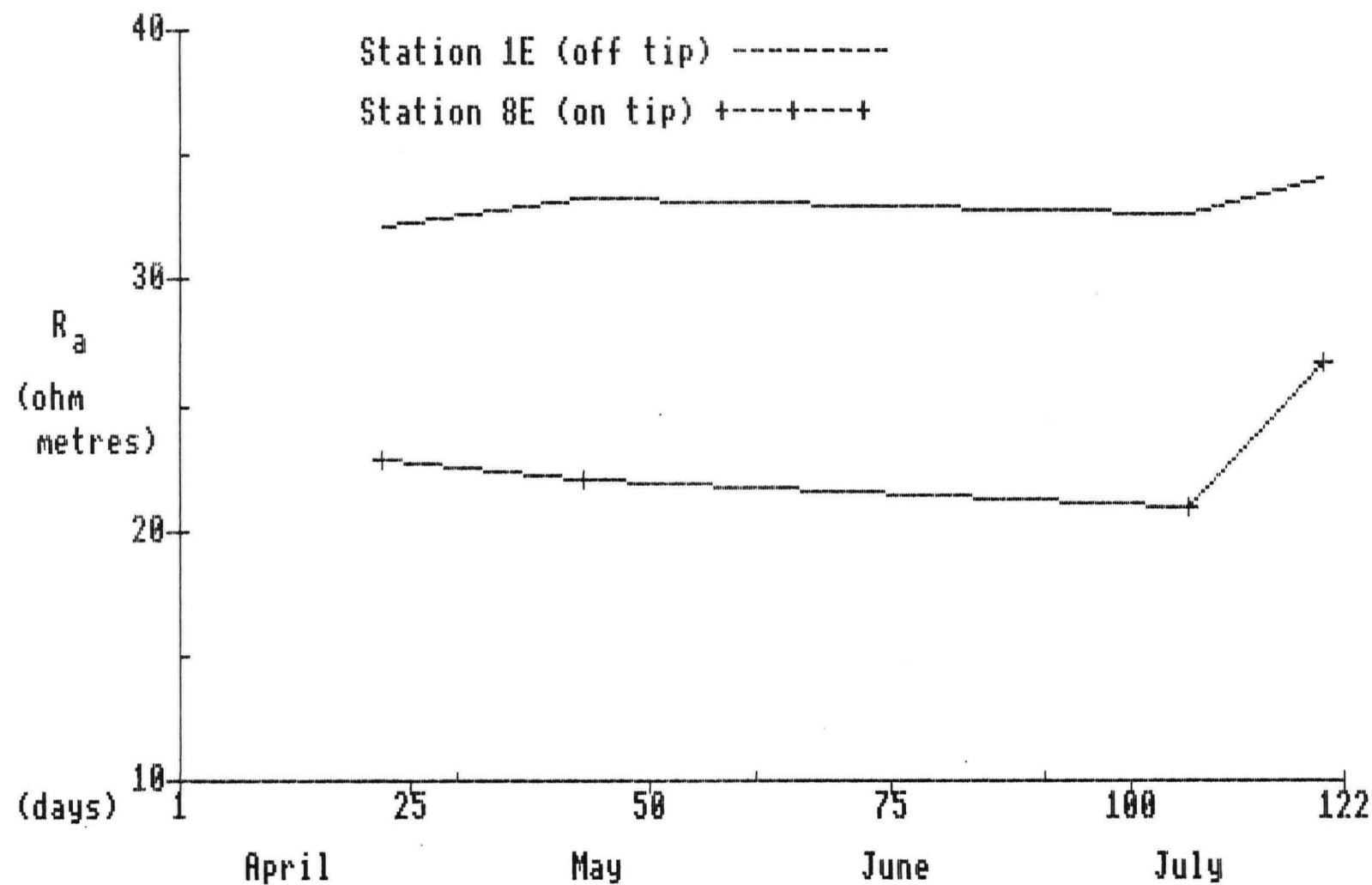


Fig. 4.3

unless achieved, could produce a variation in results.

The traverses have been used to compile a contoured plan of apparent resistivity values for a Wenner array with an electrode separation of 10 metres. Individual "broadside" traverses have been compiled for lines 4, 6, 8, 9 and 11 with electrode spreads perpendicular to the traverse line. Traverses C, E, and G have been selected and plotted individually and, together with the compiled "broadside" traverses, are presented in Figs. 4.4 to 4.11.

Traverses obtained from the line of square array soundings on Line X-X have also been interpreted using the "Abbreviated Mapping System".

#### 4.3.3.2 Discussion

##### The Traverses

The resistivity of the host and fill materials are compared in Table 1. The resistivity contrast is in the region of 2:1, as was also determined on the trial traverses. The higher contrast, on Line 9 (3:1) and Line 6 (2.2:1) have been caused by unusually high peaks on the resistivity profile near the north boundary. The variation in resistivity, as displayed by the Sample Standard Deviation, has also been influenced by these peaks on the host material. The variation on the fill material is less marked, the standard deviations are in the range 3-5.

West LINE C Wenner Resistivity Traverse (a=10m) 22 July 1984 East

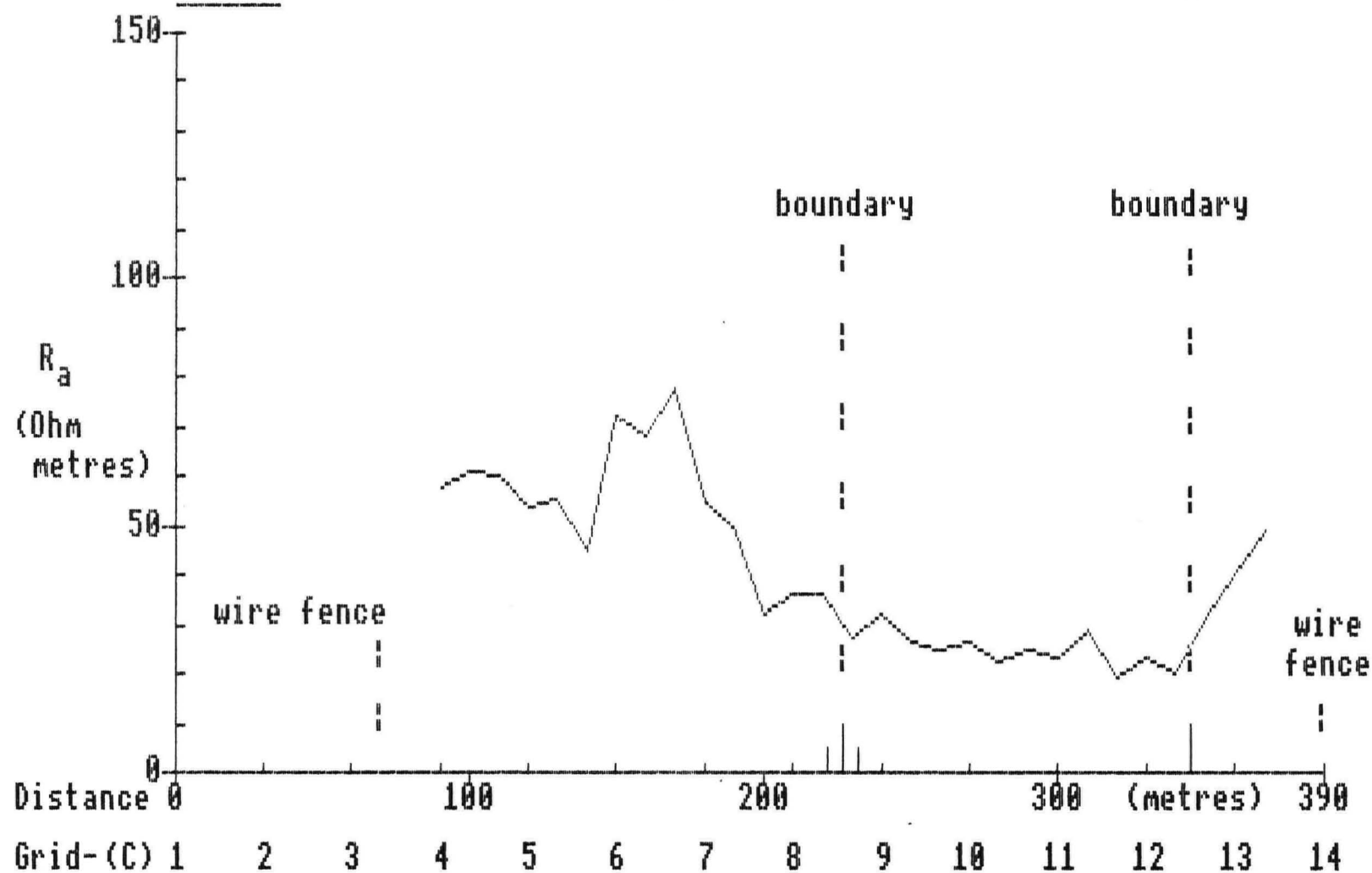


Fig. 4.4

West      LINE E      Wenner Resistivity Traverse      ( $a=10m$ )      22 April 1984      East

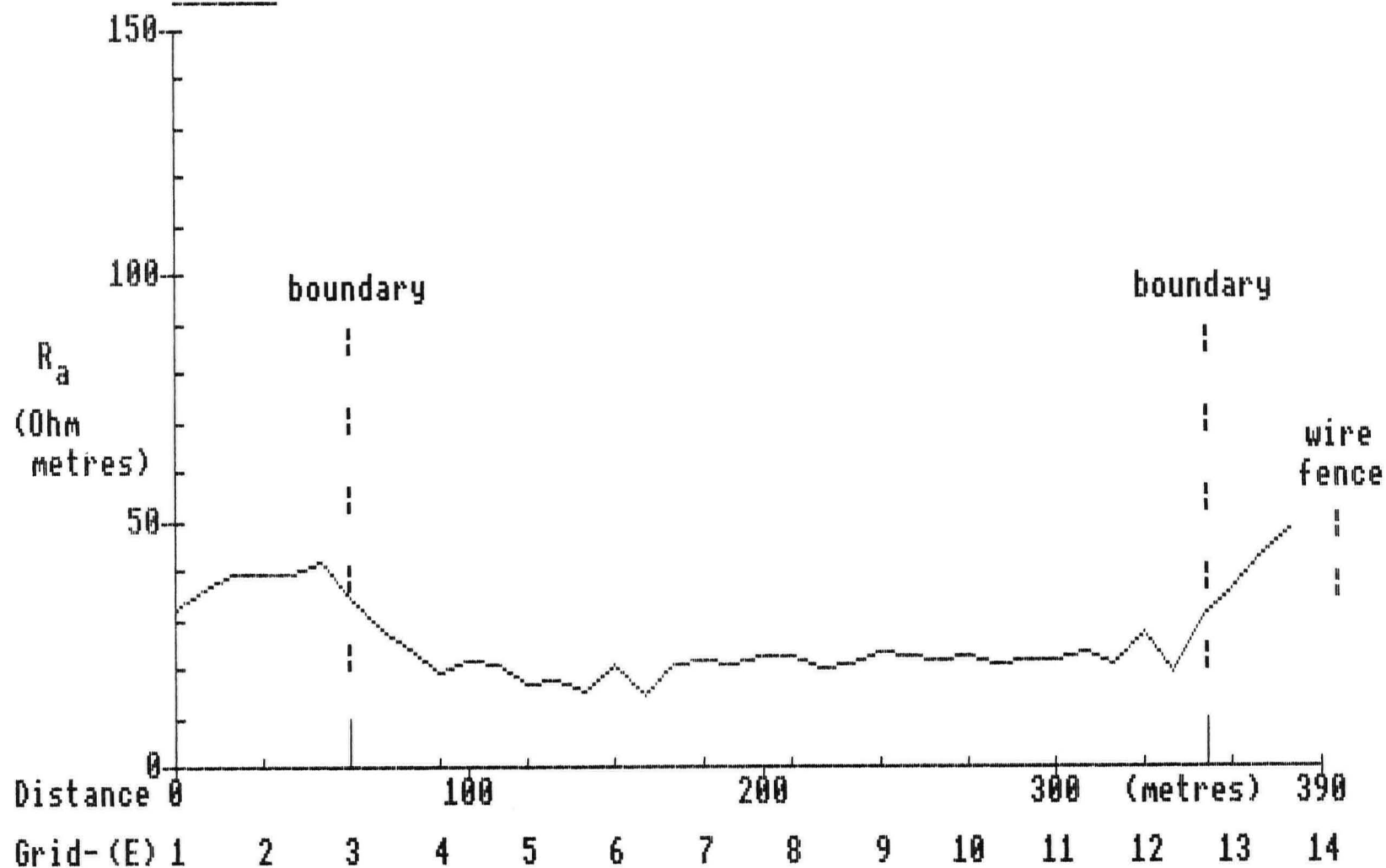


Fig. 4.5

West      LINE G      Wenner Resistivity Traverse      (a=10m)      6 May 1984      East

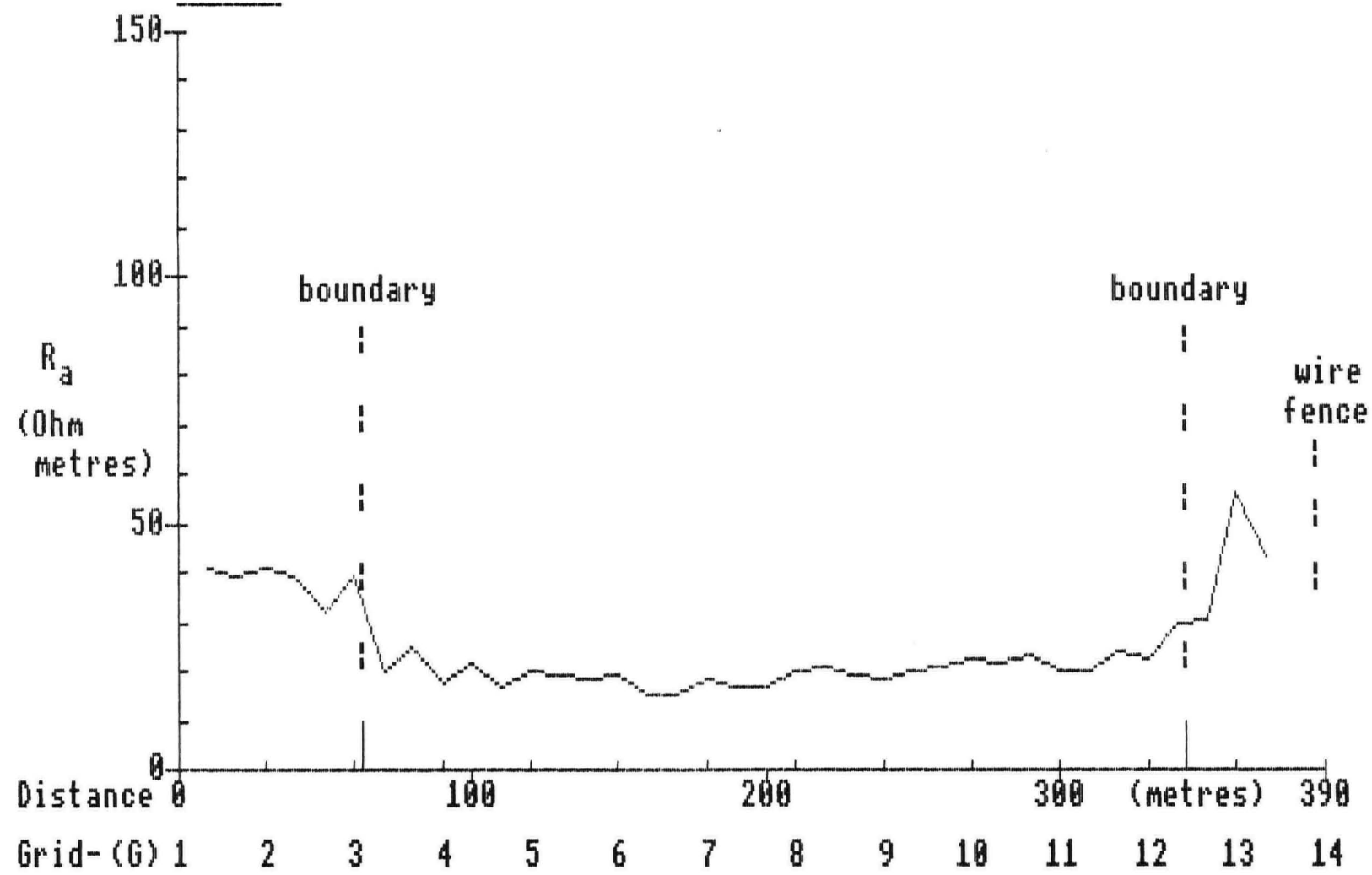


Fig. 4.6

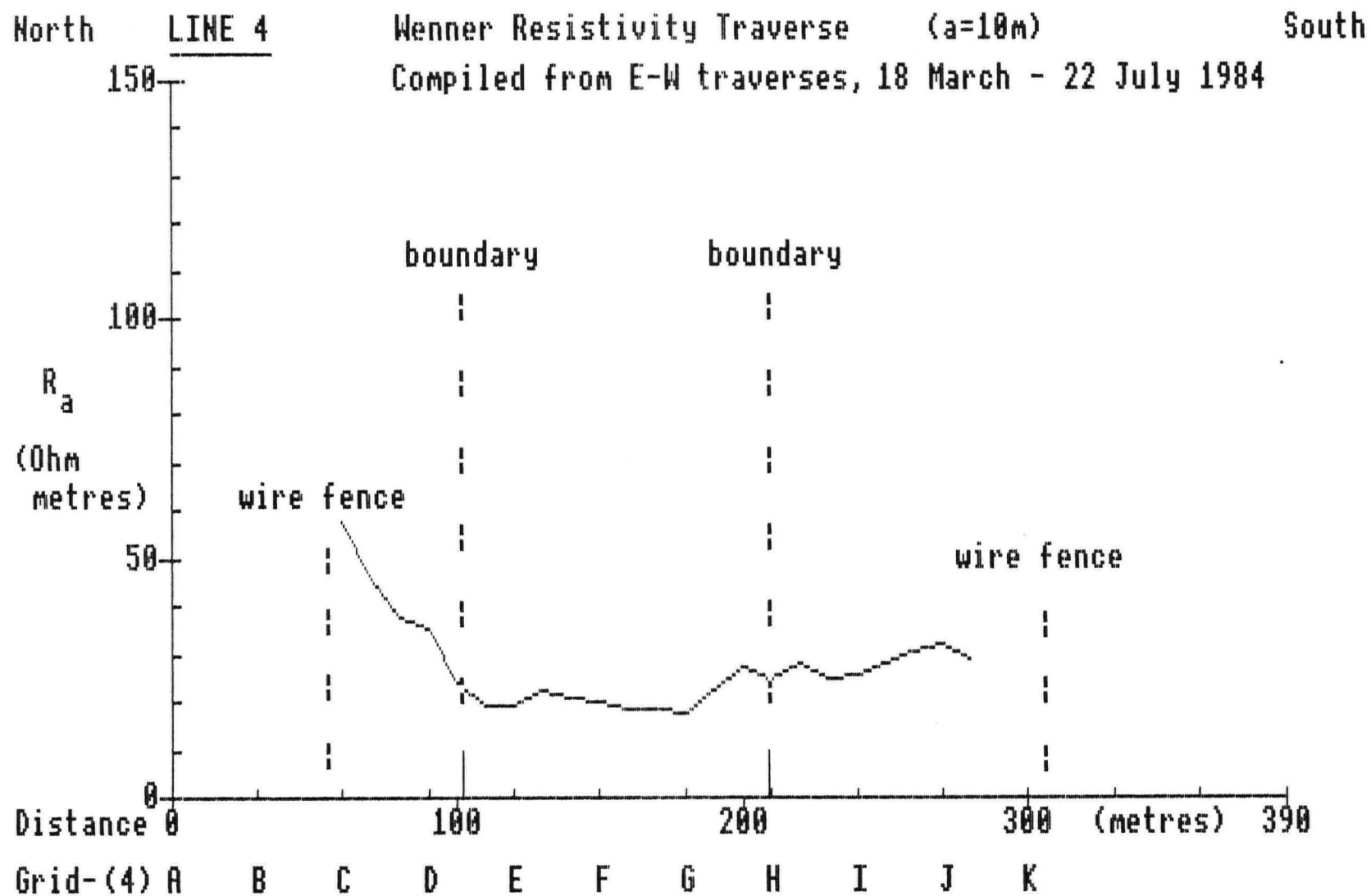


Fig. 4.7

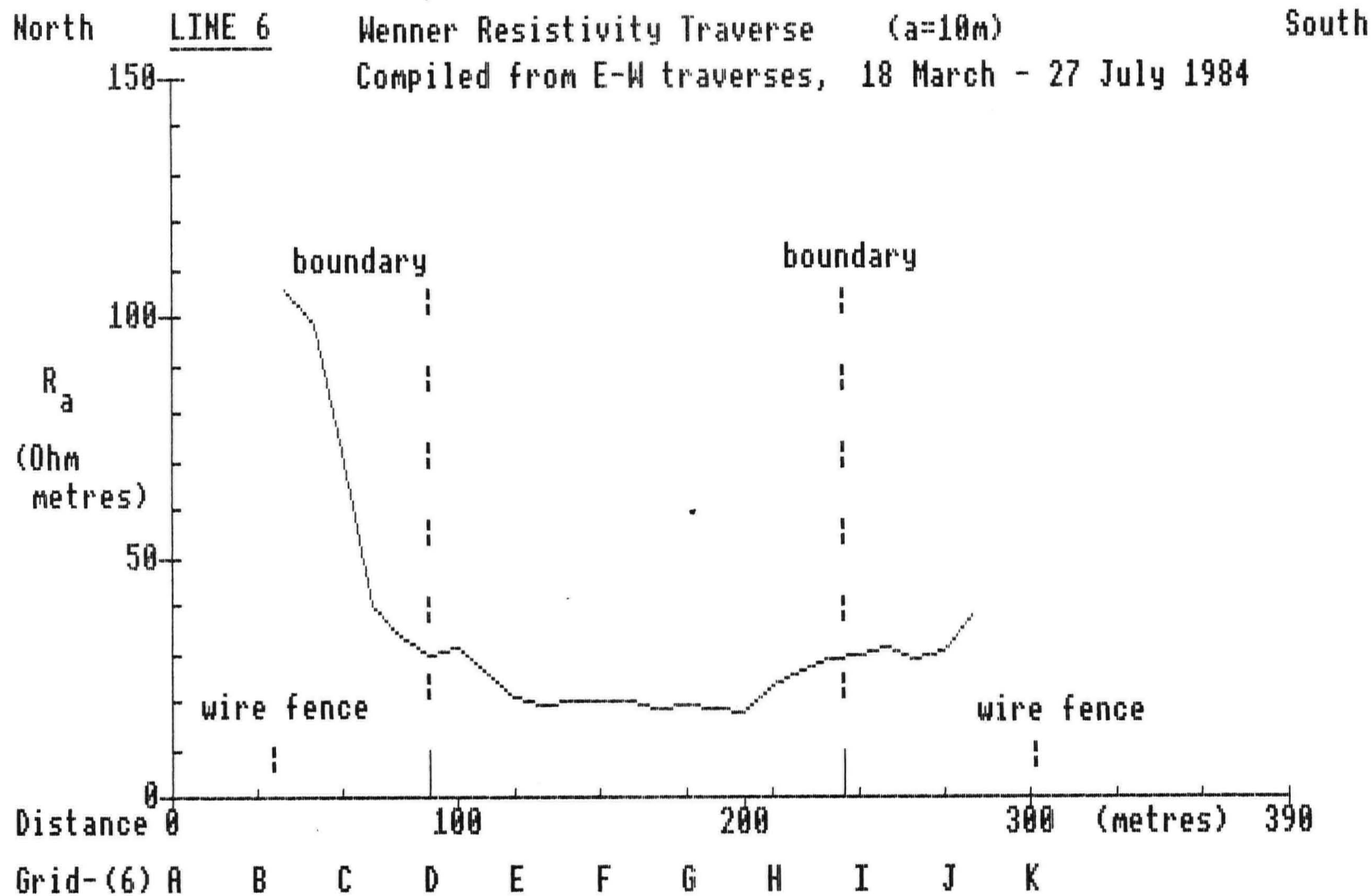


Fig. 4.8

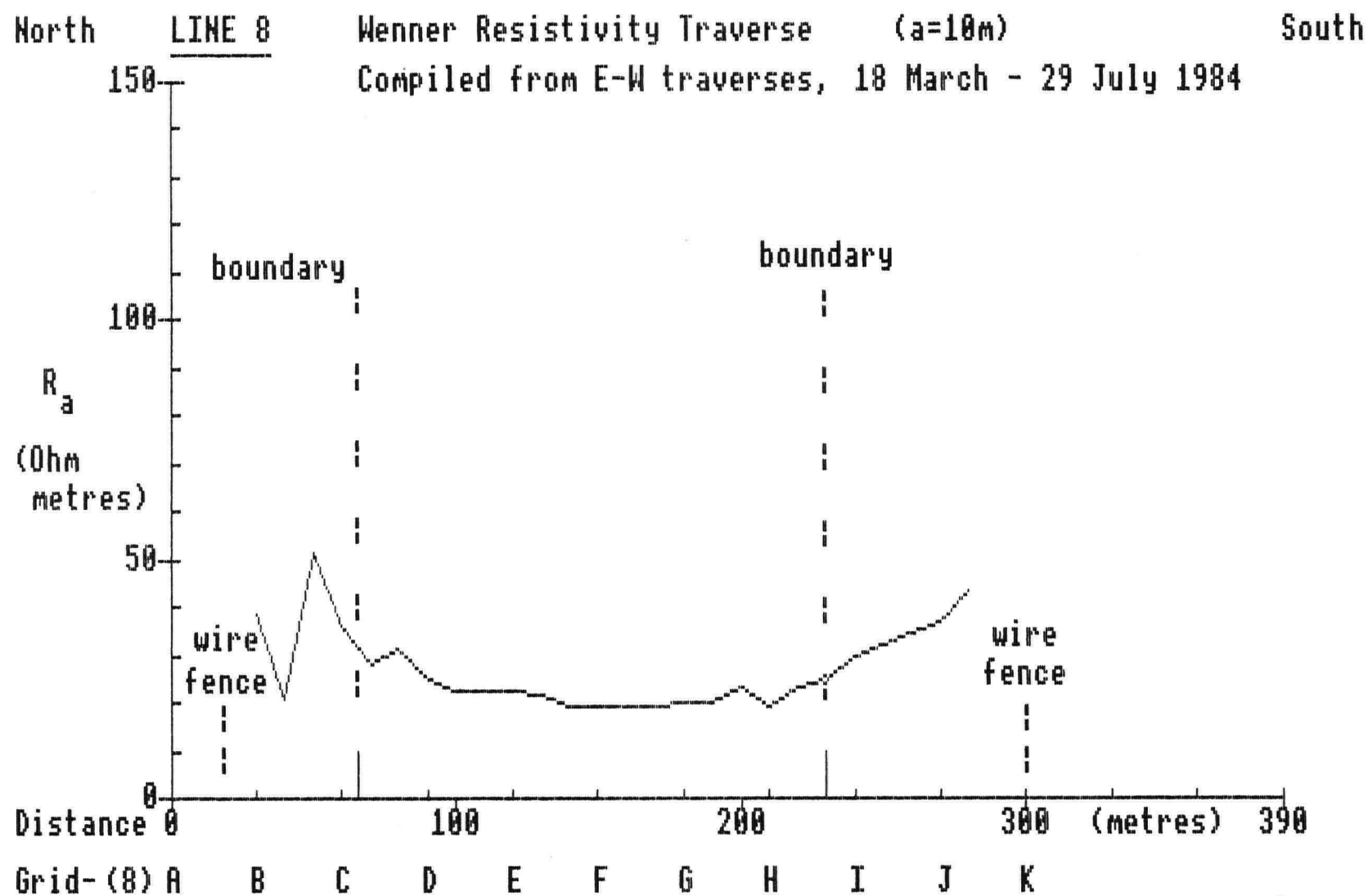


Fig. 4.9



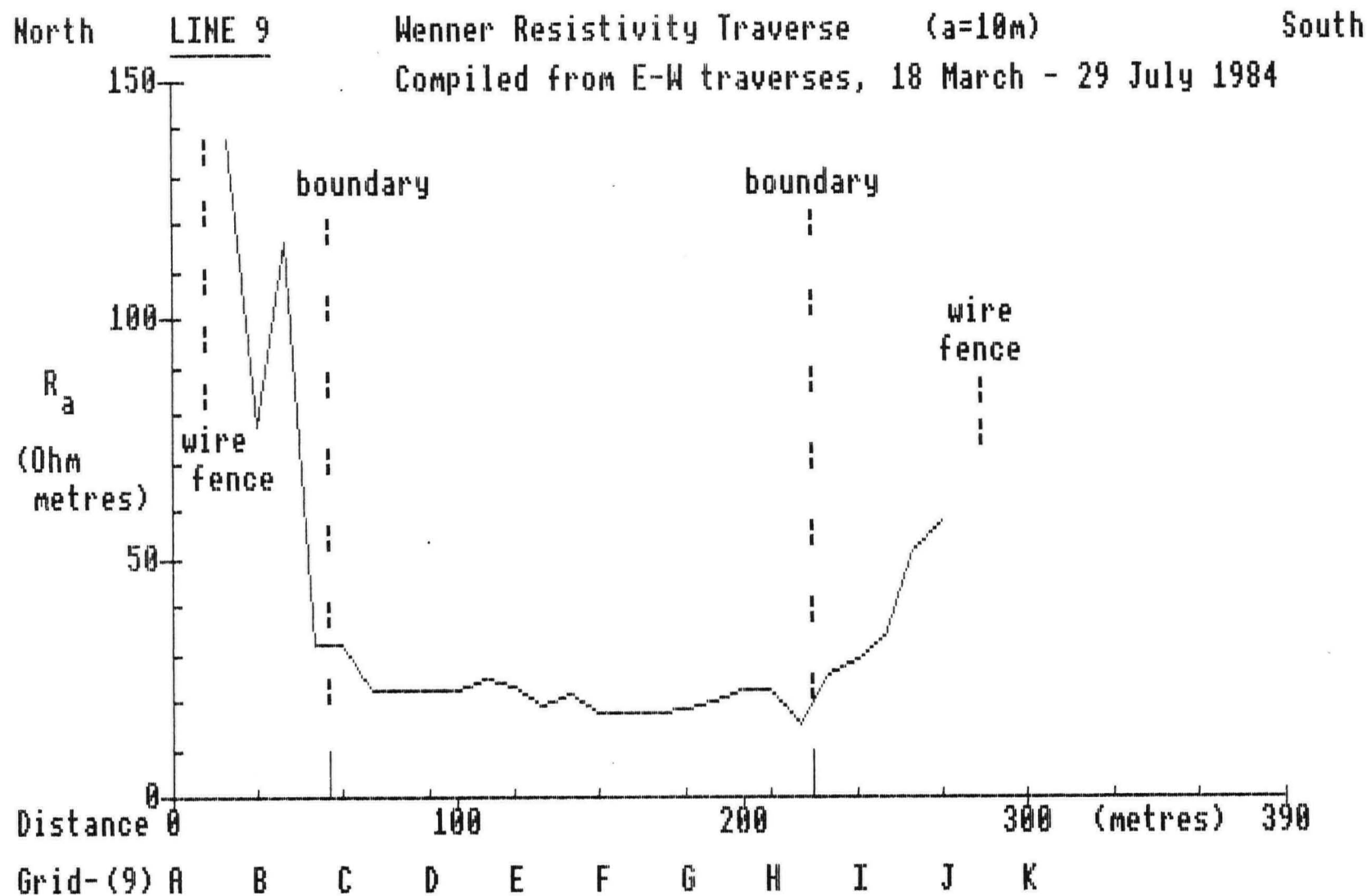


Fig. 4.10

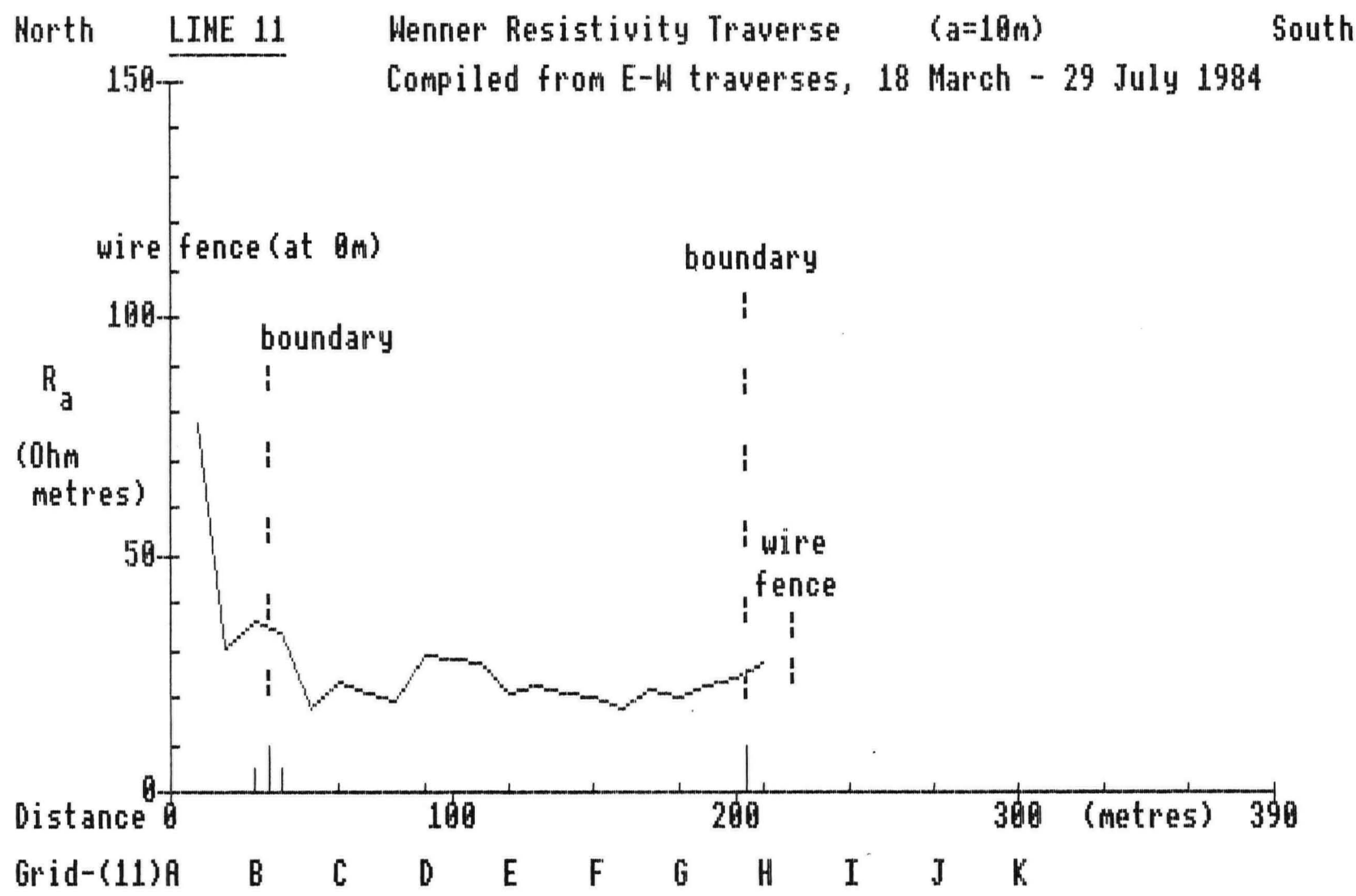


Fig. 4.11

TABLE 1  
RESISTIVITY TRAVERSES (WENNER)

Traverse No.	HOST		FILL		Contrast	Remarks
	Resistivity ohm m	*Standard Deviation n-1	Resistivity ohm m	Standard Deviation n-1		
4	34	10	21	3	1.6:1	
6	51	29	23	5	2.2:1	High resistivity anomaly on north boundary
8	36	9	23	4	1.6:1	
9	63	41	21	3	3.0:1	High resistivity anomaly on north boundary
11	-	-	23	4	-	Insufficient measurement on host material
C	52	14	25	4	2.1:1	Line oblique to boundary
E	39	5	22	3	1.8:1	
G	40	7	20	3	2.0:1	

\* Includes variation due to the system

Inspection of the north-south profiles reveals more marked peak and trough features on the northern boundary than on the southern boundary which are shown on the compiled "broadside" traverses (see in particular traverse 8, Fig. 4.9). The gradient of the profile is also greater on the northern boundary than on the southern boundary on all north-south traverses. The shape of the profiles over the east and west boundaries on traverses E and G are similar (Figs. 4.5 and 4.6).

The theoretical response of a Wenner traverse has been calculated using the method outlined in Telford et al (op. cit.). The geoelectric model used and the calculated response are shown on Fig. 4.12 (Model 1) and comprises a vertical boundary of infinite extent separating materials of 40 ohm metres and 20 ohm metres. These values of resistivity were chosen from the values of apparent resistivity produced by the traverses, in particular the east-west traverses (Lines C, E and G). These values are obviously influenced by the resistivity of the underlying till, but this is the "bedrock" to both the fill and host material and therefore does not contribute to the relative values of apparent resistivity across the boundary.

The form of the resistivity profile shows some agreement with the western ends of Lines E and G. In particular, the widths of the transitional zone between  $\rho_1$  and  $\rho_2$  on the calculated profile and field profile are both approximately 30m.

### Resistivity Model 1

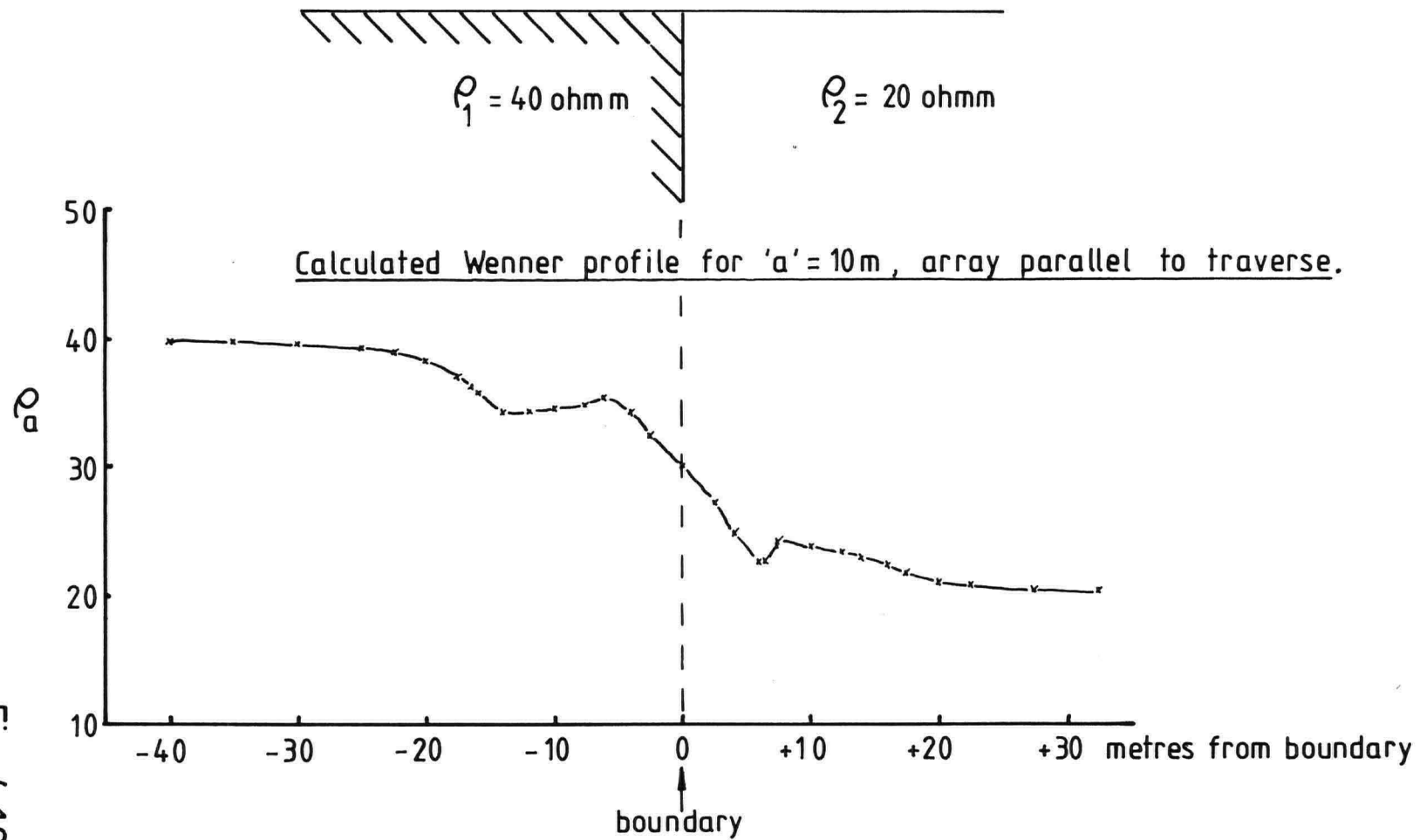


Fig. 4.12

The position of the boundary does not coincide with any distinctive feature on the theoretical profile, which is a limitation of the Wenner configuration when used for profiling.

It appears that the boundary can be simplified to a vertical interface. This would appear to be reasonable, intuitively, as the length of the sloping part, projected to the ground surface, is small compared with both the electrode separation and the station interval (see Fig. 2.7).

The geoelectric model used to examine the form of the Wenner profile across a boundary (Model 1, Fig. 4.12) is obviously greatly different from the geological models presented in Chapter 2 (Figs. 2.7 and 2.8). The response of a more realistic, but still simplified geoelectric model of two layers was therefore calculated. The model is shown on Fig. 4.13 (Model 2).

The clay cap and the sand and gravel host material have been given similar resistivities because, as noted previously, the clay cap was actually a clayey sand and gravel in both areas investigated by hand augered boreholes across the boundary.

The fill material and the underlying till have also been equated. The layer thicknesses on Model 2 are a compromise. The sand and gravel has been made thicker than shown on the geological section (Fig. 2.7) to coincide with the fill thickness.

### Resistivity Model 2 (boundary)

Calculated Wenner resistivity ( $a=10\text{m}$ ), and EM 31 responses.  
(actual responses - Lines E and G - in brackets)

Wenner response  $\triangleright$  74 ohmm. (40 ohmm.)  
EM 31 response  $\triangleright$  36.6 ohmm. (38-58 ohmm.)

41 ohmm. (20 ohmm.)  
16.9 ohmm. (6-9 ohmm.)

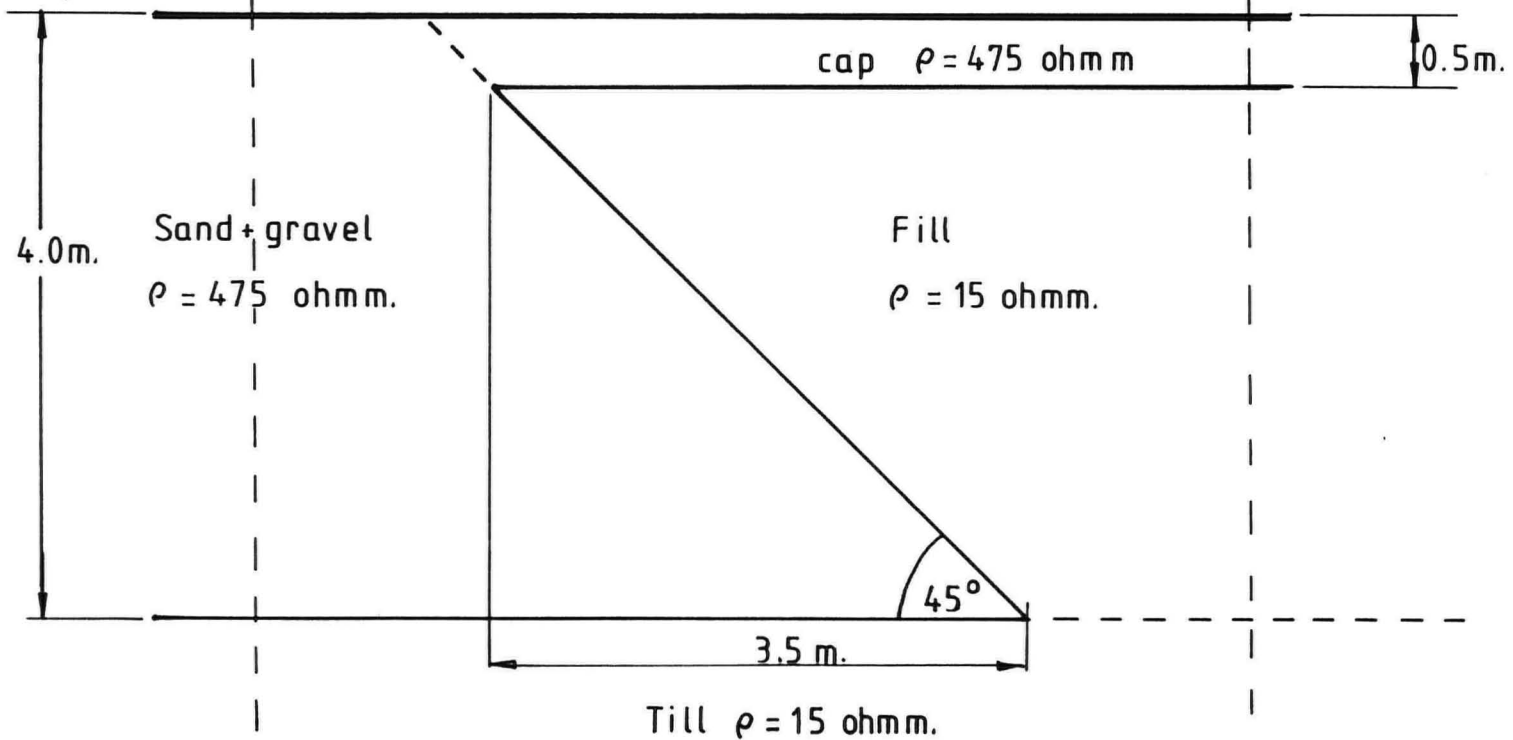


Fig. 4.13

The values of resistivity shown on Model 2 are those which give the best correlation between the two layer calculated response and the typical values obtained with the Wenner traverses, but which remain within the range of values considered realistic for the materials. An indication of the top layer resistivity was obtained from the apparent resistivity indicated by close spaced electrodes in resistivity soundings.

The calculated response for Wenner array with 'a' = 10m are shown on the Model, together with typical values obtained from the actual traverses (Line G).

It is clear that the agreement is not good; the calculated responses are higher than the field response. It is likely that the field response is influenced by a deeper third layer, not included in the model.

The model was refined further by assigning different values of resistivity to the cap and host material (see Model 3, Fig. 4.14). The resistivity values were obtained from soundings 9E and 2F (see later section). The calculated response is lower than with Model 2. There is good agreement with the field response over the fill, but the calculated response over the host material is too low.

An interpretation of a square electrode array traverse on Line X-X was attempted using the Abbreviated Mapping System method described by Broadbent and Habberjam (1971), although as stated previously, the design of the master curves is not



### Resistivity Model 3 (boundary)

Calculated Wenner resistivity ( $a=10\text{m}$ ), and EM 31 responses.  
(actual responses - Lines E and G - in brackets)

Wenner response = 14 ohmm. (40 ohmm.)  
EM 31 response = 27.8 ohmm (38-58 ohmm)

18 ohmm (20 ohmm)  
21 ohmm (6-9 ohmm)

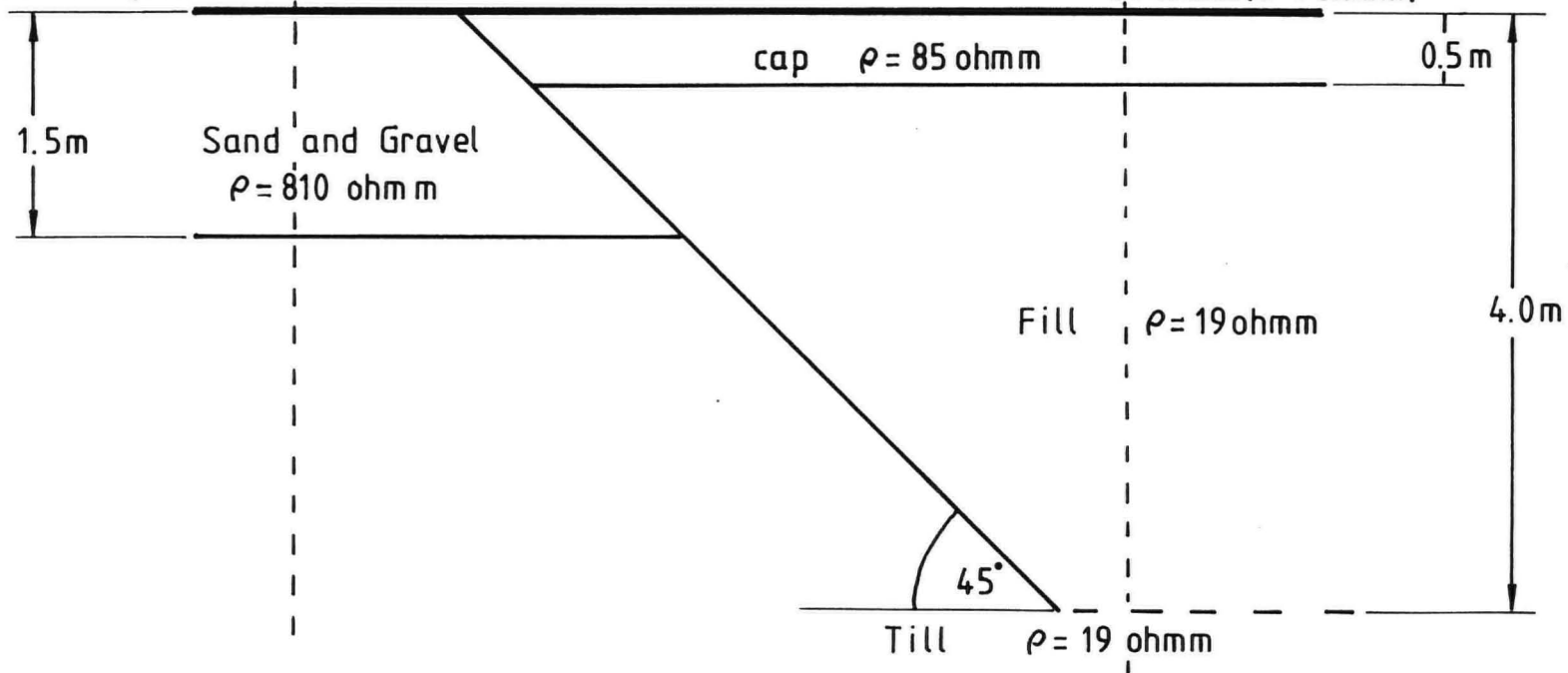


Fig. 4.14

ideal. The method was tried initially using "a" values of 4m, 6m, 10m and 15m. The curves produced from the 4m and 6m traverses were irregular, probably as a result of the variation in surface layers. Only the 10m and 15m curves were therefore interpreted. Figs. 4.15 and 4.16 show the mean apparent resistivity values plotted on a log scale against horizontal distance normalised with respect to the electrode separation distance. The results of the interpretation are shown on the Figures. The procedure, as outlined by Broadbent and Habberjam, is as follows:

Values of  $\rho_2$  and  $\rho_1$  are obtained from regions well away from the interface and the value of  $\rho_2/\rho_1$  is obtained. The half width is calculated from the difference in horizontal distance between the points at which the resistivity equals  $(\rho_1 \rho_2^3)^{1/4}$  and  $(\rho_1^3 \rho_2)^{1/4}$ . The dip angle of the interface is then estimated from the master curves (Figs. 6a and 6b in the paper by Broadbent and Habberjam). The dip angle derived from the  $a = 10m$  curve was between  $22.5^\circ$  and  $30^\circ$ . The dip angle from the  $a = 15m$  curve was approximately  $45^\circ$ .

The two values should be the same. The fact that they differ show that the field conditions do not match the assumed model. In particular, there is a clay cap which provides a third layer and the interface does not extend infinitely downwards, as assumed by the model. The condition assumed in the model would be more closely satisfied for the traverse produced with the smaller 'a' values. However, the smaller electrode spacings produce a more noisy signal, thus, there are conflicting requirements for successful

LINE X-X Square array traverse, "a" = 10m.  
 $\log \rho_a \times \text{distance} / 'a'$  metres

$$\frac{\rho_2}{\rho_1} = 2.3$$

$$\frac{w}{a} = 1.45$$

dip =  $22.5^\circ - 30^\circ$  (from Fig.6, Broadbent & Habberjam)

$\frac{x}{a} = 0.9$  (from Fig.7, ), predicted outcrop

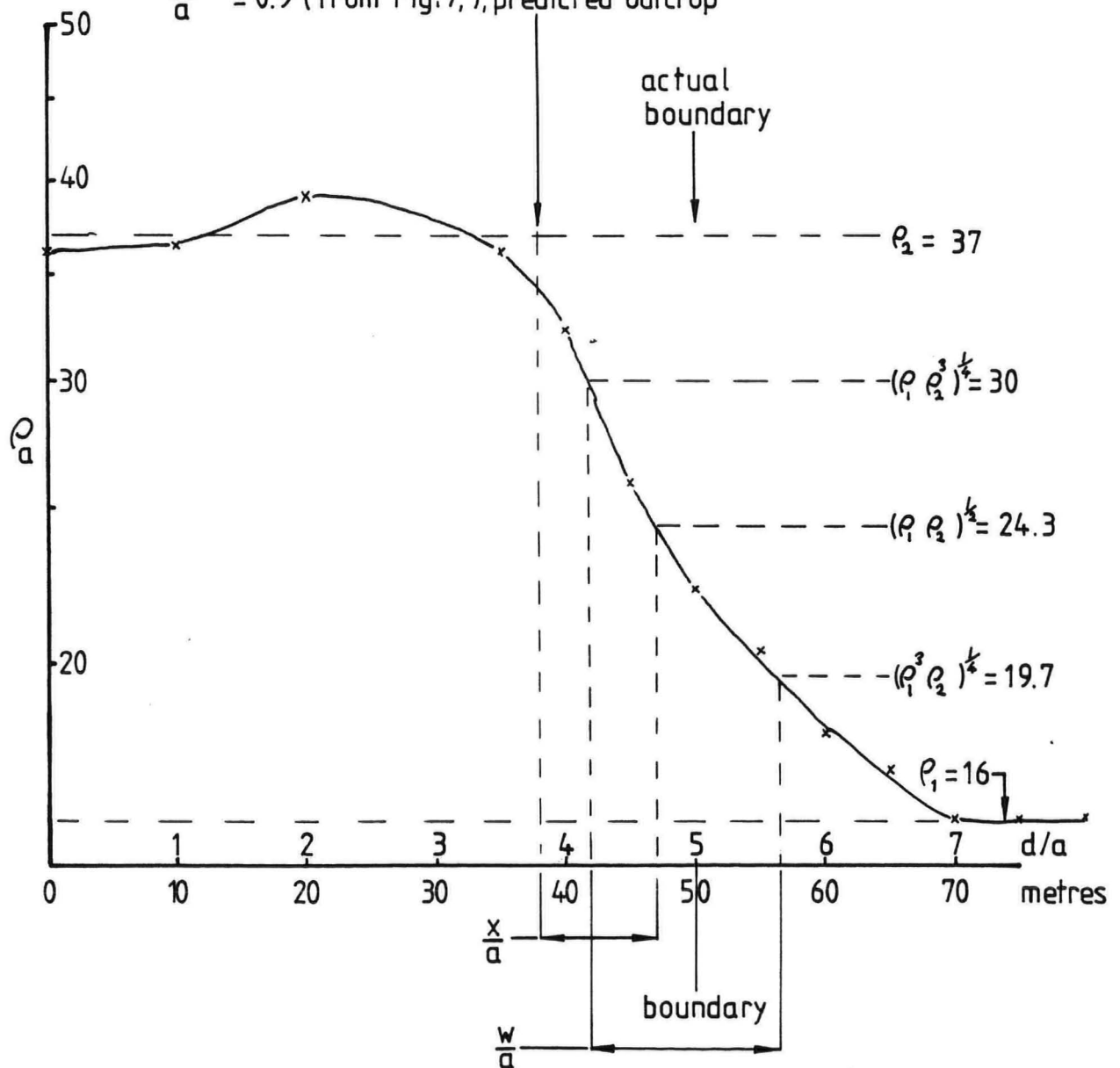


Fig. 4.15

LINE X-X Square array traverse, "a" = 15m

$\log \rho_a \times \text{distance} / 'a' \text{ metres}$

$$\frac{\rho_2}{\rho_1} = 2.2$$

$$\frac{w}{a} = 1.1$$

dip =  $45^\circ$  (from Fig. 6)

$\frac{x}{a} = 0.3$  (from Fig. 7) predicted outcrop

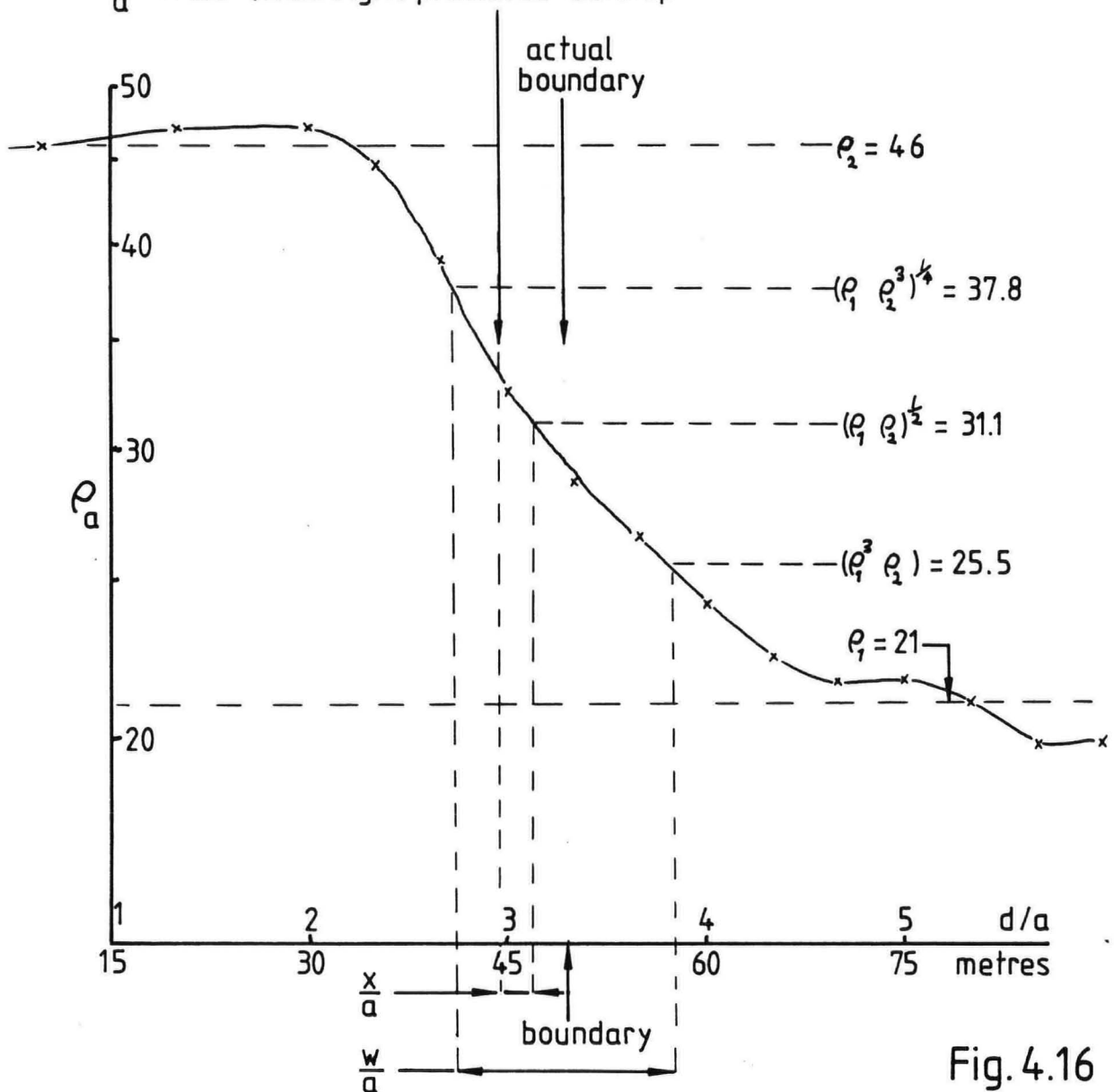


Fig. 4.16

interpretation on this site which cannot be satisfied. However, the estimate of dip derived from the  $a = 15\text{m}$  profile gives a sensible result.

The outcrop of the boundary was also determined from the Abbreviated Mapping System of Broadbent and Habberjam. The position is shown on Figs. 4.15 and 4.16. It is clear that the analysis using the profile compiled from the  $a = 15\text{m}$  traverse predicts the position of the boundary to within 6m of the topographic expression of the boundary. The accuracy of the analysis derived from the  $a = 10\text{m}$  profile was not so good (12m error). It was found that the accuracy decreased even more with smaller 'a' values, presumably because the quality of the profiles was inferior at these electrode spacings.

#### Contoured Apparent Resistivity Plan

In the absence of a satisfactory quantitative interpretation for the traverses, they are best used qualitatively. The contoured apparent resistivity plan has, therefore, been produced. The plan showing iso-resistivity values is presented in Fig. 4.17. The contour interval is 10 ohm m. It is apparent that the topographic expression of the tip boundary coincides with the contour distribution on the west, north and east sides. The iso-resistivity contours on the southern side do not match the boundary very well. It is fortuitous that the 30 ohm m contour closely follows the tip boundary, but this is a function of the chosen contour interval and electrode separation.

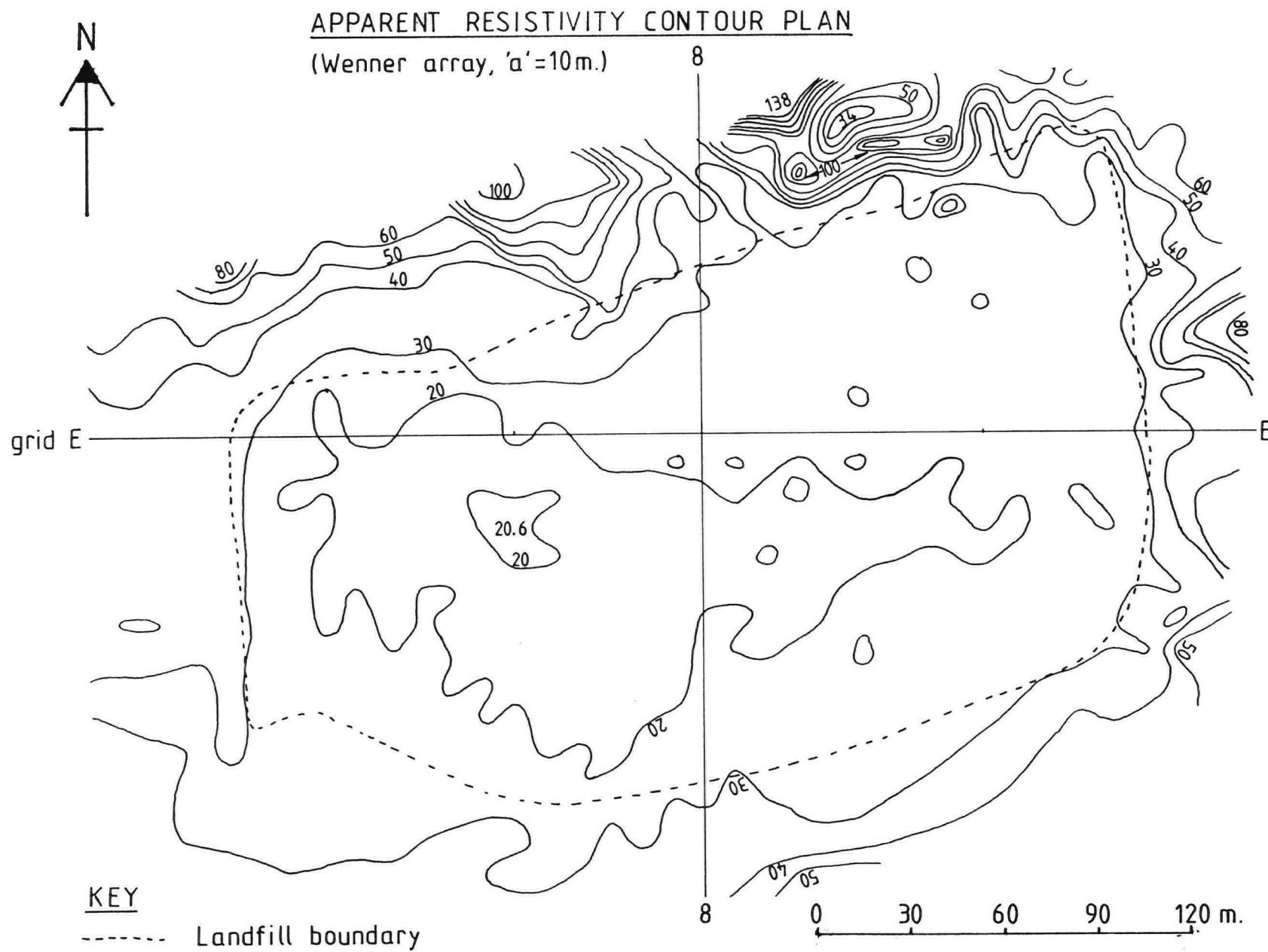


Fig. 4.17

Wenner traverses, "a" = 10 m. 22 - 29 July 1984

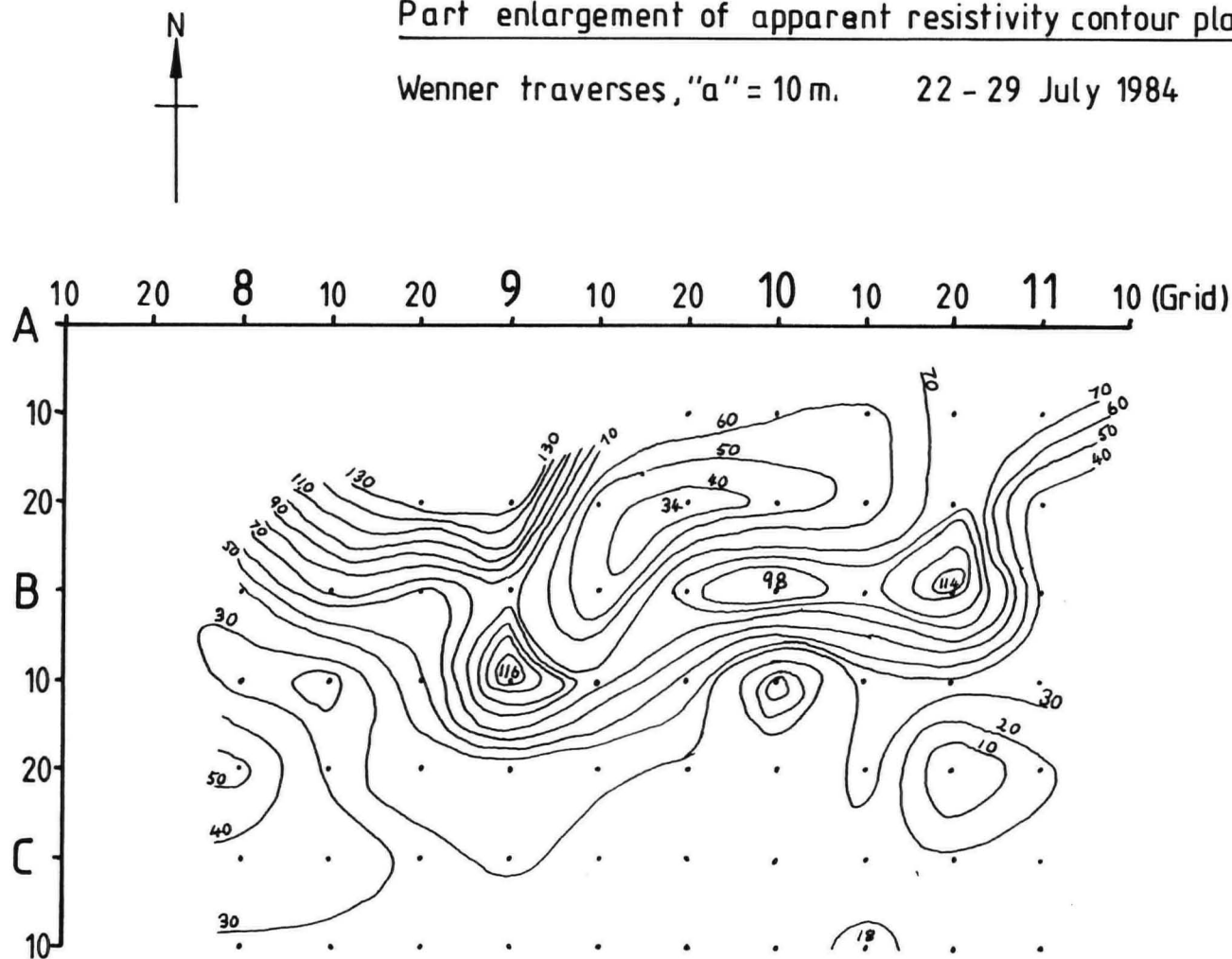


Fig. 4.17a

The gradient of resistivity is larger in the region of grid lines 8 to 11 on the north boundary. The contoured plan reveals the relationship between the high and low resistivity in this region. There appears to be a "peak" and a "ridge" at 9B+10m, and 10B respectively, with values in excess of 100 ohmm. In addition there are "troughs" of low resistivity at 8B+10m, 9+20mA+20m and at 11A+20m. These may be produced by leachate plumes issuing from the tip; this area is the lowest topographically and so leakage in this region would not be unexpected. Other features on the north boundary are probably due to variations in lithology, for example, the broad resistivity high at 6B+10m. A similar feature is present on the east boundary at 13+20m,D.

The choice of contour interval affects the shape of the features previously discussed. A balance has to be achieved between an interval which is close enough to reveal the features of interest, and one which is wide enough to mask "noise" arising variation at shallow depth which tends to be a feature of filled ground.

The Standard Deviations of the traverses which are in the range 3-5 (Table 1) suggest that a 5 ohm metre contour interval would show unwanted variations. A trial plot using this interval confirmed that the general trends which were apparent using a 10 ohmm interval were partly obscured.

The difference in apparent resistivity gradients between the southern and northern sides of the site may be caused by variation in the resistivity of the host material. The



resistivity highs, which are a feature of the northern margin, could be gravel lenses. This would concur with the description of the Smug Oak Gravel given by Gibbard (op. cit.).

The lower resistivity gradient noted on the southern boundary could be due to a mixing between the fill and host material, for example as a result of slumping of the excavated face during tipping. It could be caused alternatively by leachate infiltration into the host material, but this appears less likely because, from what is known of the dip of the underlying clay, it would appear to require leachate movement up-dip. The more likely explanation is that resistivity gradient is affected by the reduction in thickness of the sand and gravel on the southern edge. The depth of the waste material would also be less on the southern boundary, if it replaced a deposit which thinned southwards, as discussed in Chapter 2 and shown on Fig. 2.8.

#### 4.3.4 Conclusions

Small electrode spacings give rise to noisy results on this site. A spacing which is larger than required from a consideration of the depth to the target layer, gives a smoother profile, but one which still retains a contrast of 2:1 between the host material and the fill.

The total width of the transitional part of the profile is no greater than the equivalent part of a calculated profile run across a vertical boundary, and there is some similarity in the forms of the theoretical and field profiles. The boundary therefore appears to be "seen" as a vertical boundary, and this is a result of the comparatively large electrode spacing used.

The width of the transitional zone on the profile is generally 30m. Therefore the position of the boundary can only be determined to an accuracy of  $\pm 15\text{m}$ . Although a guess could be made that the boundary is centred in the transitional zone, the results show that this is not always the case. The calculated response of a Wenner traverse each side of the form of boundary shown in Model 2 does not agree with the field response. It appears that a third layer is required in the model.

Quantitative interpretation of a square array profile using the "abbreviated mapping system" of Broadbent and Habberjam (op. cit.) gives sensible results for the prediction of the dip angle if an electrode spacing of 15m is used. Smaller

spacings produce unrealistic results which are attributed to the effects of "noise". 15m appears to be the optimum electrode spacing for this method. Larger spacings would tend to be influenced by deeper material which would produce a section which did not comply with the infinitely dipping interface assumed by the model. The prediction of the boundary position (the surface outcrop of the interface) is again closer with the 15m electrode interval than with the 10m interval.

The north-south traverses show a distinct difference between the form of the resistivity profile across northern and southern boundaries. There is a much greater contrast on the northern boundary compared with the southern boundary. This feature is displayed better on the contoured apparent resistivity plan. One possible explanation is that the boundary between the fill and host material is dipping more gently on the southern side of the landfill than elsewhere. The geological evidence presented in chapter two tends to support this assumption. A reduction in resistivity of the host material would have the same effect on the resistivity profile.

The method will not necessarily produce the same degree of success on other landfills. The lithology of the host material and the ground water regime are critical.

In summary, the resistivity traverses are best used qualitatively and the best form of presentation for this purpose is the contoured apparent resistivity plan. In

favourable conditions, i.e. where the boundary approaches an infinitely dipping interface with respect to the electrode spacing, the quantitative method of Broadbent and Habberjam can be considered.

#### 4.4 Resistivity Soundings (Depth Probes)

##### 4.4.1 Method and Interpretation Techniques

Soundings were taken at grid numbers 6F, 9E and 9+10mE+20m on the tip and at 2F and 6I+20m off the tip. A correlation with the true lithology was available from boreholes at 2F and 6F.

The Schlumberger electrode configuration was used in all cases. Two sets of readings were taken at 9+10mE+20m corresponding to the electrode spread orientated in a north-south and an east-west direction. This provided a check on the lateral variation in the fill material.

The variation in apparent resistivity between the two sets of readings was slight in comparison to what appeared, by inspection of the resistivity curves, to be the natural scatter on the depth profile, although this is only a subjective assessment. The readings varied from the mean by a maximum of 9%. Subsequent soundings were conducted using one set of readings only. Knight et al (1978) also found little difference between readings obtained with two sets of electrode arrays at right angles using the Wenner configuration on a landfill site near Sidney, Australia.

It is often reported that the Schlumberger electrode configuration is less susceptible to lateral variation in the ground (for example, Griffiths and King 1981). This is because the ground over which the potential is measured

remains the same for most of the readings, until the potential electrodes have to be spread further apart to enable a potential difference to be measured.

An overlap of two readings was provided when it was necessary to change the potential electrode separation. The curve used for interpretation was smoothed if there was an abrupt step in the curve at these change over points; however, usually there was no step in the curve.

The soundings were interpreted using the ABEM VES Interpretation program, run on a Hewlett Packard H.P. 85 computer. The procedure requires that a likely model of horizontally layered ground is introduced into the computer in terms of layer thicknesses and resistivities. The program then generates a resistivity curve from the model. This curve is compared with the field curve and successive alterations are made to model layer thicknesses and resistivities, by an iterative process, until the model curve matches the field curve.

The interpretation thus produced is a horizontal layered geoelectric section which could produce the field curve, but it is not a unique solution. (The principle of equivalence demonstrates that combinations of different layer thickness and resistivities can produce the same resistivity curve). Non-horizontally layered ground would not be interpreted accurately. The final interpretation is, therefore, dependant on the form of the initial model to some extent. It is important that the initial model should resemble the

ground which is being surveyed.

The models introduced during the interpretation procedure were based on information from the boreholes. For soundings 6F and 2F (which were coincident with boreholes) the thicknesses were known and the resistivities were estimated. The program enables the operator to fix either one or all of the layer thickness in the model and this facility was used where there was a borehole control. The iterative process then only altered the resistivities of the layers until a match was obtained between the two curves.

#### 4.4.2 Presentation and Discussion of Results

The sounding curves are shown on Figs. 4.18 to 4.22. The interpretation of the curves, in terms of layer thicknesses and resistivities is also included. Fig. 4.23 is a summary diagram.

##### Sounding 6F

Sounding 6F was obtained during August 1984. It was interpreted using the fixing facility on the program to nominate layer thicknesses, which were obtained from borehole log 6F.

There is a number of possible geoelectric models which can be derived from the borehole log. Initially a 6 layer model was used which split the top 0.9m into three layers 0.3m thick and which also included a 0.1m water layer at 4.0m. Thus every lithological unit was introduced in the geoelectric model. The resistivities, produced by the program in order to match the field curve, were not realistic using the 6 layer model. For example, the layer at 0.3m to 0.6m depth was assigned a resistivity of 2 ohm metres, while the materials above and below, which are also essentially sandy gravelly clays, were assigned resistivities of 275 and 73 ohm metres. The best fit curve using nominated layer thickness is the 5 layer model shown on Fig. 4.18.

It is apparent from this interpretation that the clay cap to the fill has a dry "crust" and a significant granular



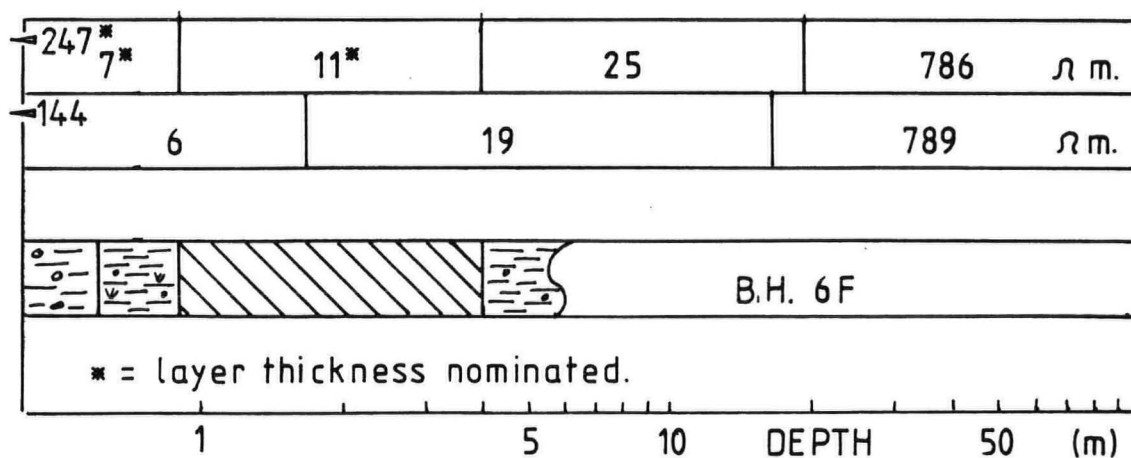
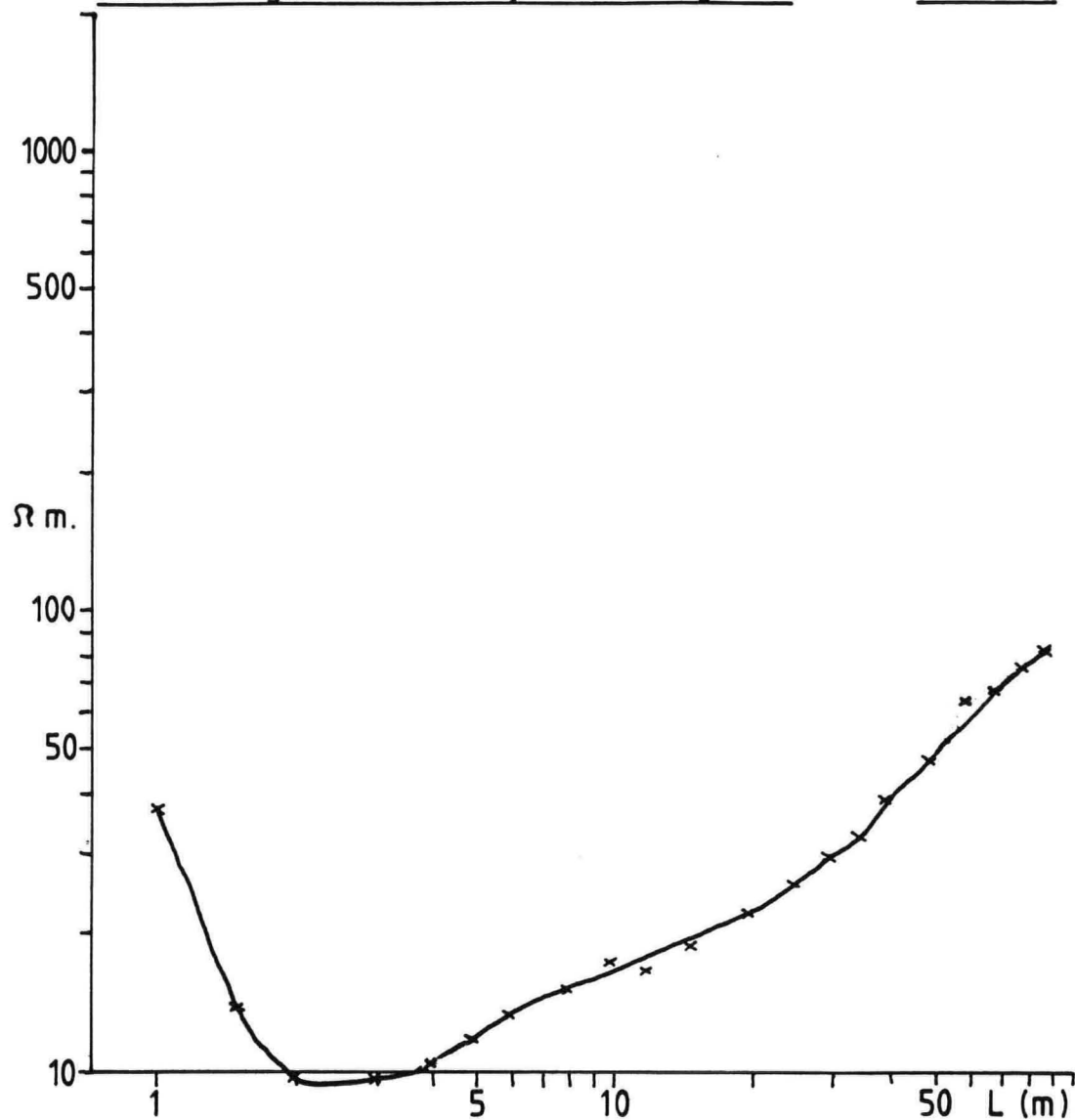


Fig. 4.18

content, as 247 ohmm is a high resistivity value for a pure clay. This agrees with observation in the field of a rapidly developing hard dry surface during the summer. The low resistivity of the lower part of the clay cap (7 ohmm) is probably caused by a combination of a higher moisture content and the inclusion of decaying organic matter containing a concentration of conductive salts (this is confirmed by the borehole log). The interpretation suggests that the resistivity of the fill is 11 ohmm.

The material with an indicated resistivity of 25 ohmm and a thickness of 15.7m is the till forming the base of the tip. The material with a resistivity of 786 ohm m at a depth of 20m may be the lower gravel layer (the Westmill Gravel).

An interpretation of 6F without fixing any parameters, but starting with a clay cap thickness of 0.3m, not surprisingly, produced a good match to the field curve, but it did not agree with the known ground profile. The clay cap was assigned a resistivity of 144 ohm m. The second layer was interpreted as 1.3m thick with a resistivity of 6 ohmm. The third layer interpretation was 15m and 19 ohm m. This "free" interpretation therefore indicates the limitations of interpreting without any borehole control. It has not differentiated the fill and the till.

### Sounding 9E

Sounding 9E (Fig. 4.19) which is also on the fill material, was obtained in June 1985. It was interpreted using the five layer model, resulting from 6F, as the start model. Although the resistivity curves 6F and 9E are dissimilar, and therefore indicative of different ground, the general model of clay cap over fill over clay would apply.

The interpretation suggests that, in comparison to 6F, the clay cap is reduced in thickness to 0.4m (see Fig. 4.23). A reduction in the thickness of the clay cap is possible. The omission of a desiccated surface layer may be explained by the different survey dates (the survey was carried out in June 1986, whereas the sounding for 6F was obtained in August 1984).

The second, third and fourth layers effectively have been given identical resistivities (18-20 ohm metres), so that the geoelectric section is reduced to three layers with the middle layer thickness, representing the fill and till, being 17m. In this situation, therefore, the thicknesses assigned by the interpretation program to the layers within the second geoelectric unit are arbitrary, and in particular, the thickness of the fill cannot be determined from this curve. The 249 ohm m material at a depth of 17m may again be the underlying Westmill Gravel.

### Sounding 9+10mE+20m

The sounding at 9+10mE+20m (Fig. 4.20) was obtained in February 1983. It is close to 9E and was also initially interpreted assuming 5 layers prior to borehole information being available. The top layer, which must be the clay cap, has been interpreted generally in accordance with 9E (0.3m and 108 ohm m). The higher resistivity value in this case would not be unusual for a gravelly clay. The granular content of the clay cap is known to vary (see Chapter 2).

The second and third layers could be combined; their resistivities are similar (28 ohm m and 24 ohm m). If this is treated as one geological unit, its thickness is 3.8m, which is very close to the thickness of the fill in BH6F.

The third layer with a resistivity of 9 ohm m and extending from 4.1m to 9.4m should be the till. However, its resistivity is lower than found elsewhere. This may be a natural variation, or it may be affected by leachate. It is only this lower resistivity value which has enabled the thickness of the overlying fill to be differentiated on the interpretation, by providing sufficient contrast.

The lowest layer commencing at 9.4m, with a resistivity of 157 ohm m, could be the Westmill Gravel, although it would have to contain a lot of sand to bring the resistivity down to its predicted value.

# Schlumberger Resistivity Sounding 9E

8/6/85

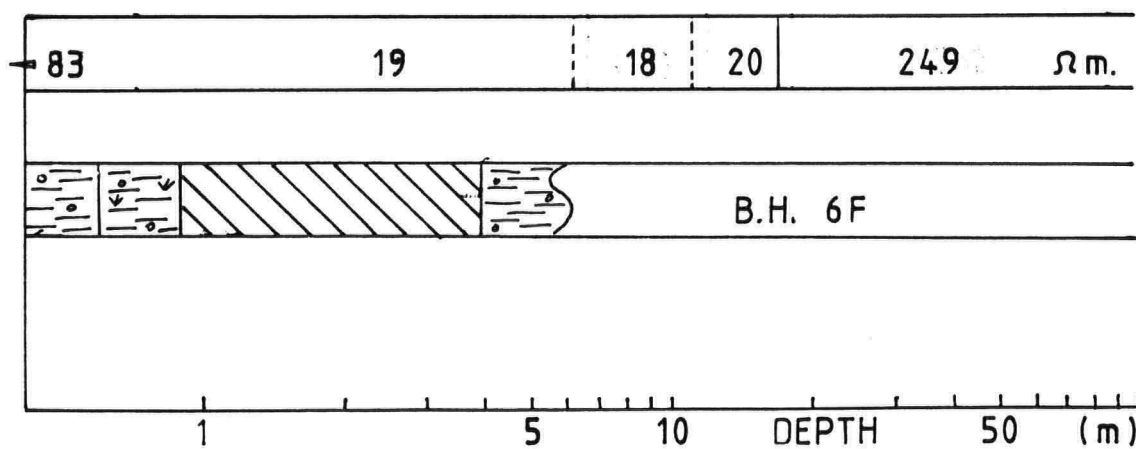
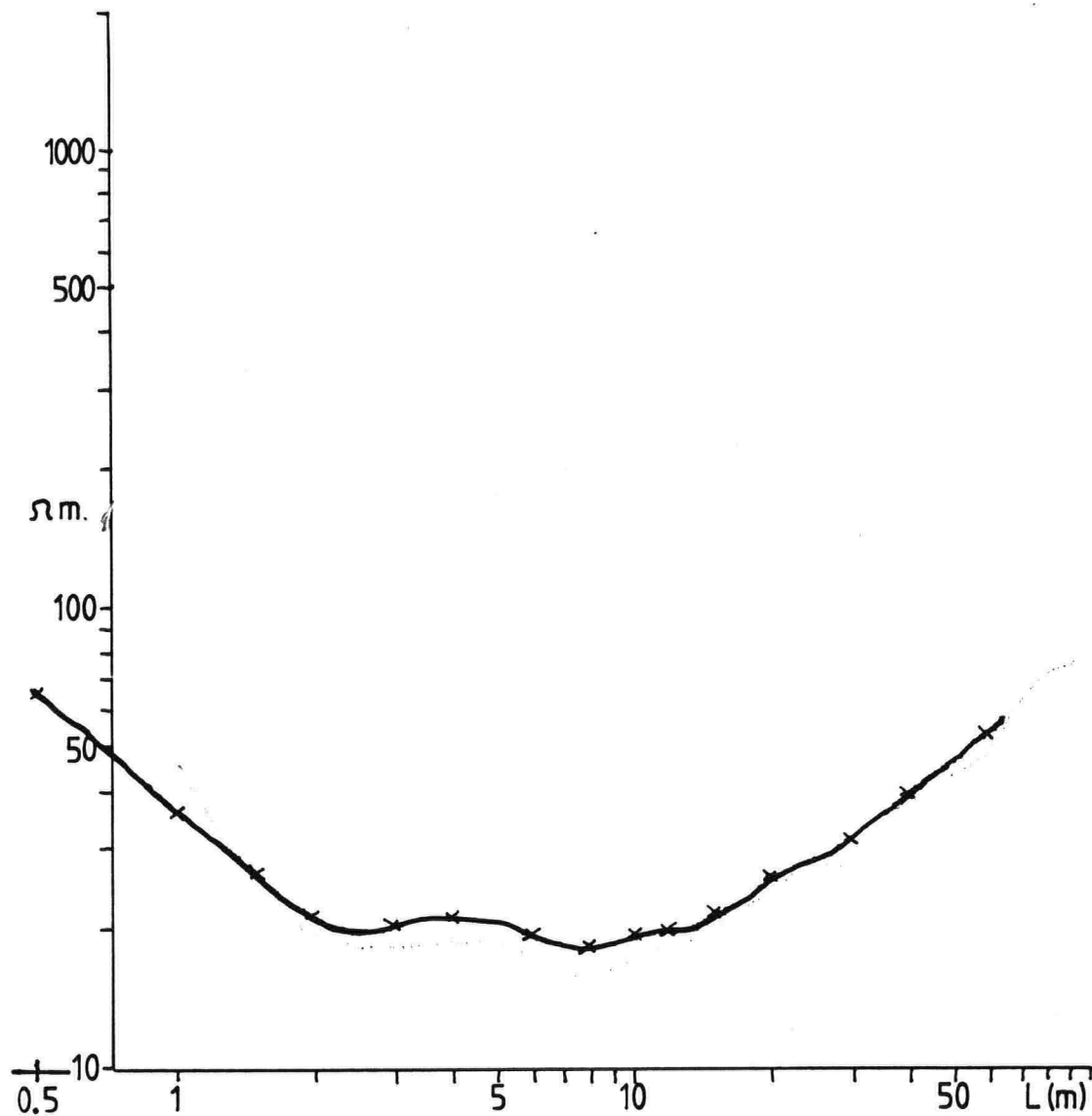


Fig. 4.19

# Schlumberger Resistivity Soundings 9+10m,E+20m.

19/2/83

(north-south and east-west electrode spreads plotted)

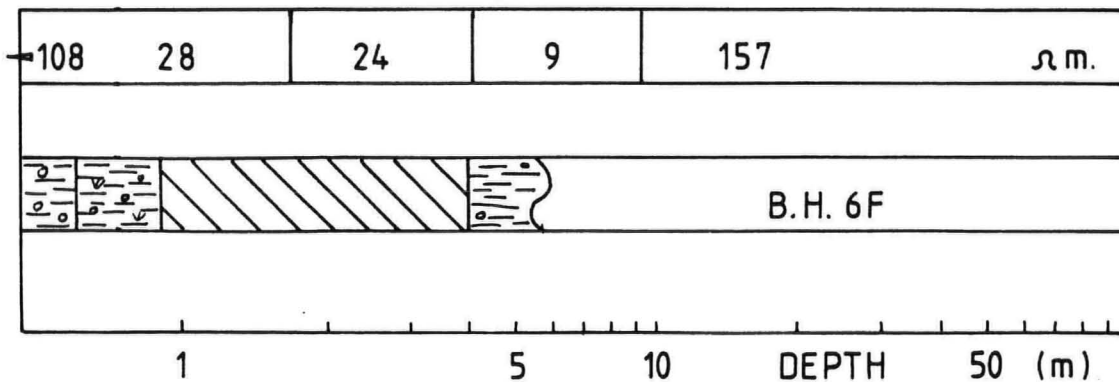
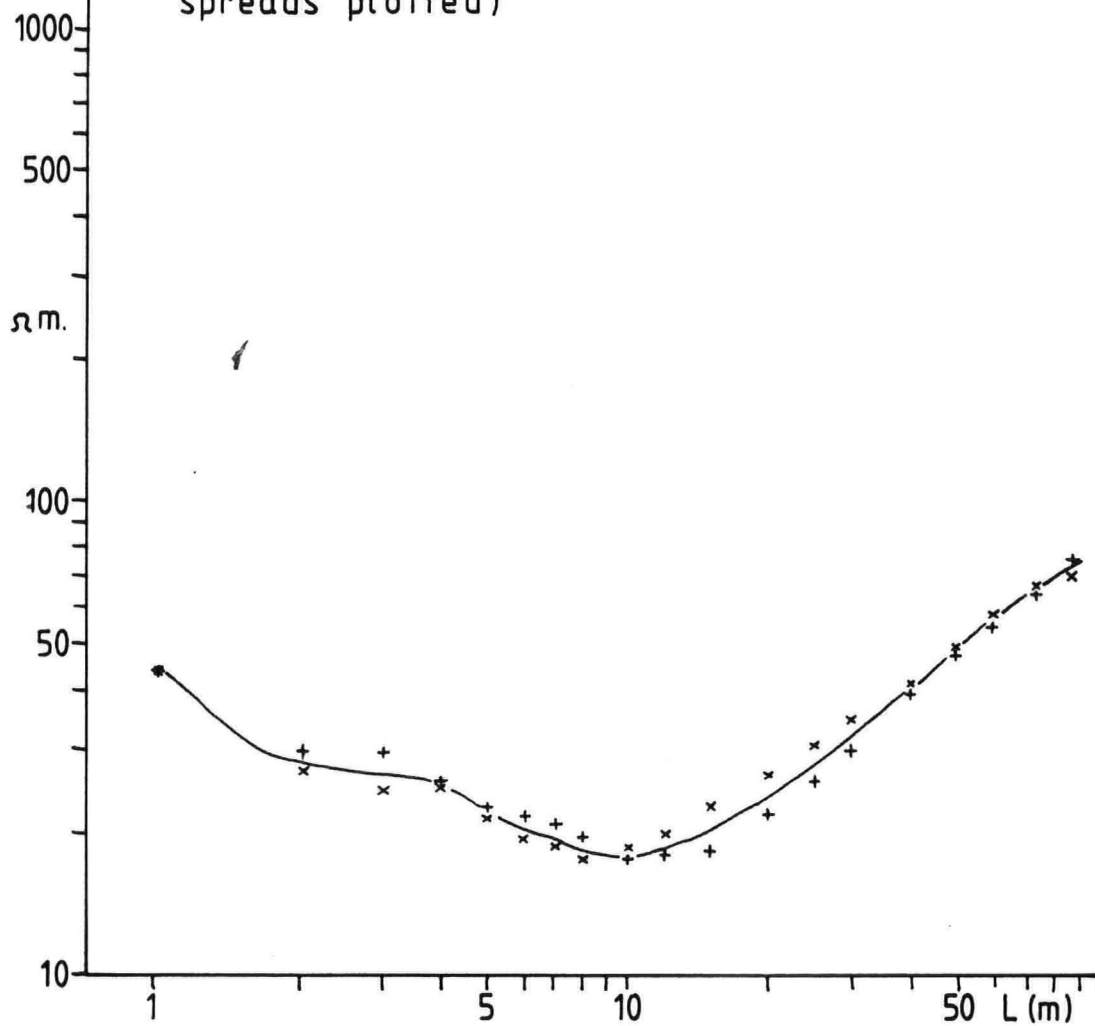


Fig. 4.20

### Sounding 2F

Sounding 2F (Fig. 4.21) was obtained in August 1984. It was taken at the location of borehole 2F, off the tip, and so information from the borehole was used for the construction of the preliminary geoelectric model. The only interpretation which fitted the field curve and the known lithological layers was the 7 layer interpretation shown on Fig. 4.21. The interpretation is detailed between ground level and 1.8 m with each lithological unit appearing on the geoelectric section. This unit is generally described as sand and gravel. The interpretation predicts that the underlying till extends from 1.8m to 5.6m. The sixth layer in this interpretation ought to be the Westmill Gravel, but it is at a shallower depth (5.6m) and of a lower resistivity (113 ohm m) than what has elsewhere been assumed to be that of gravel.

An attempt was made to reduce the number of layers in the geoelectric model. The alternative 5 layer interpretation is the best-fit alternative. The simplification has affected the top layers primarily, so that the geoelectric model does not match the known geological conditions.

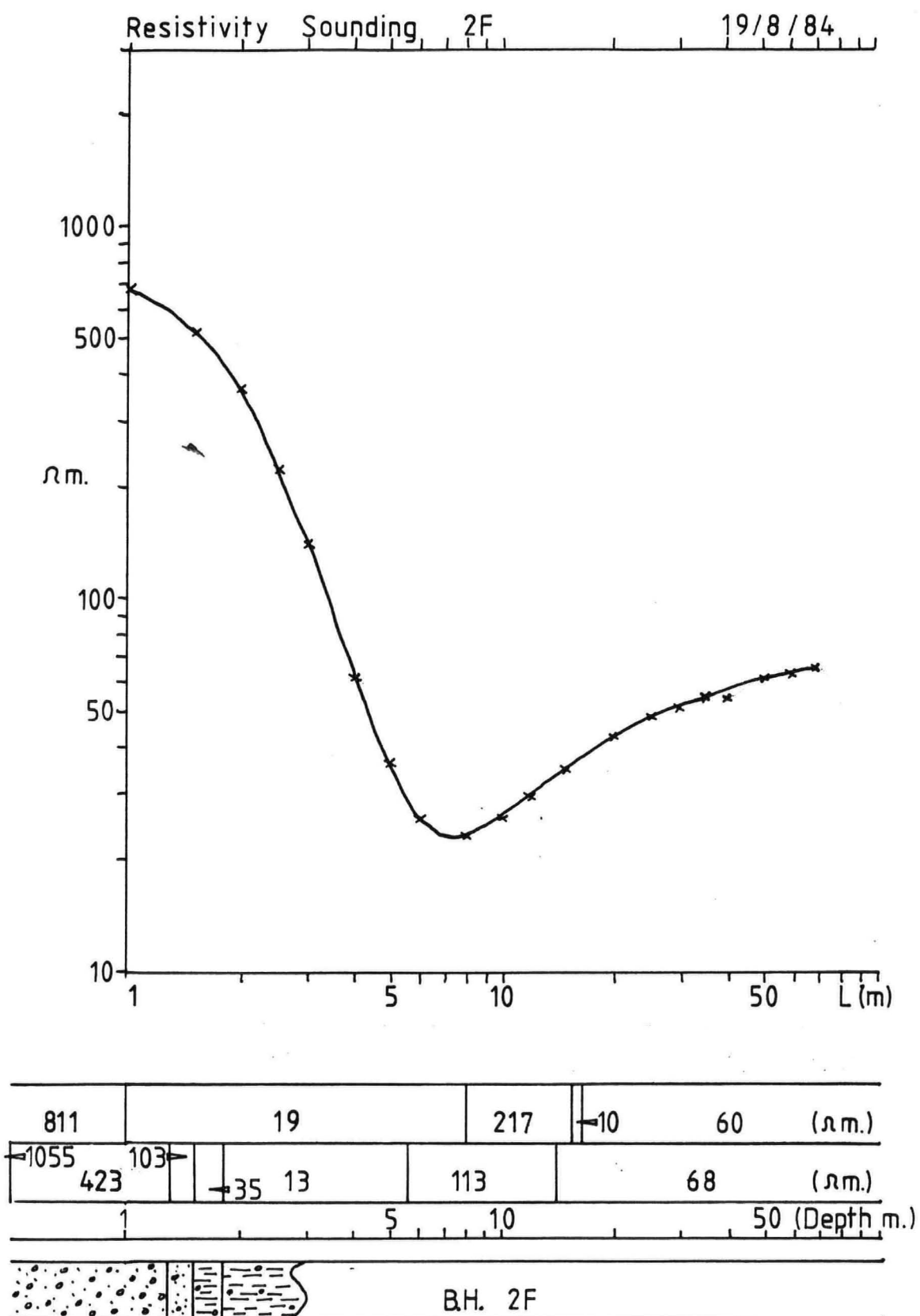


Fig. 4.21



### Sounding 6I+20m

Sounding 6I+20m was obtained in August 1984 off the tip (Fig. 4.22). A more simple four layer model fits the field curve with a general similarity to the 5 layer interpretation of 2F. A layer with similar thickness and resistivity to the layer which is known to be clay of sounding 2F is suggested by the interpretation. The sand and gravel above is not differentiated, and is assigned a resistivity of 468 ohmm. The thickness (1.2m) is slightly less than the 7 layer interpretation of 2F. A lower gravel layer is again suggested of similar depth and thickness to that in 2F, but of much higher resistivity. This may be one of the gravel lenses typical of the Westmill Gravel (Gibbard 1977).

# Schlumberger Resistivity Sounding 61+ 20m.

19/8/84

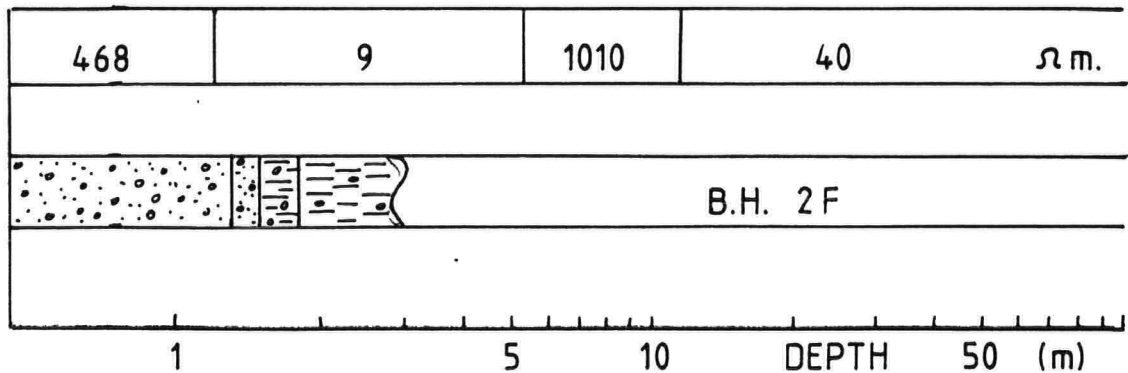
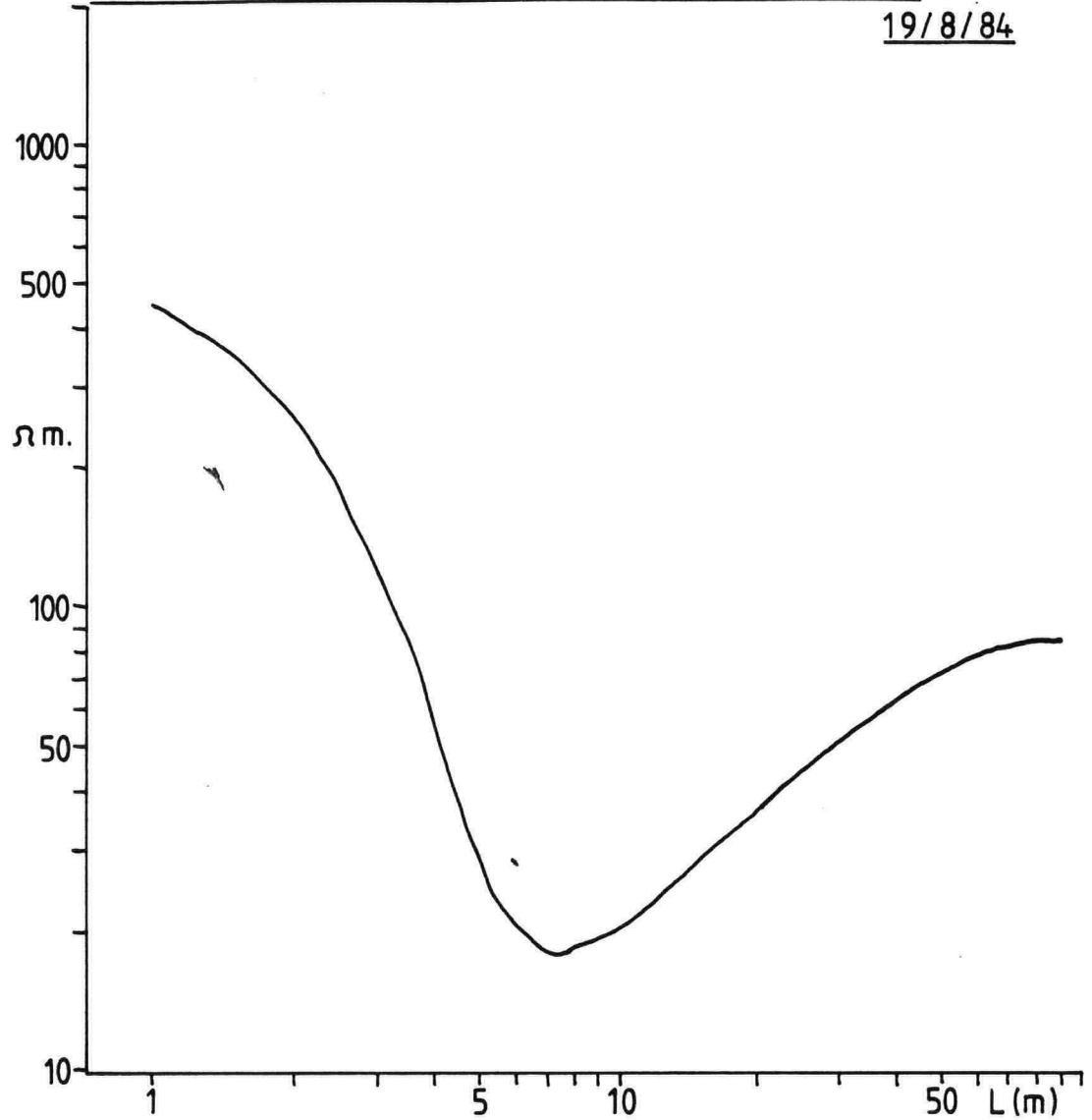


Fig. 4.22

Summary diagram of Resistivity Sounding interpretation

6F						9E				9+10m, E+20m				2F					6I+20m								
Lithology (BH 6F)	T (m)	ρ (Ωm)	T (m)	ρ (Ωm)	D	Lithology	Thickness (m)	Resistivity (Ωm)	D	Lithology	Thickness (m)	Resistivity (Ωm)	D	Lithology (BH 2F)	T (m)	ρ (Ωm)	T (m)	ρ (Ωm)	D	Lithology	Thickness (m)	Resistivity (Ωm)					
Dry gravelly clay	0.4	144	0.3	248	0	Gravelly Clay cap	0.4	83	0	Gravelly clay cap	0.3	108	0	Topsoil oversilty Sand			0.5	1065	0	Sand and Gravel	1.2	468					
Moist sandy clay + organics			0.6	7		Domestic Refuse over clay with chalk gravel (Till)	5.9	19	3	Domestic Refuse	1.4	28	1	Dry sand and gravel	1.0	811			1								
Domestic Refuse	1.3	6			1																	Sand			0.8	423	
																						Sandy clay			0.2	103	
																								0.3	35		
			3.1	11	2												2		(3.8)	(24-28)		Clay with chalk gravel (Till)	6.8	19			2
					3				3		2.4	24				3.8	13										
	15.1	19			4				4										4								
Clay with chalk gravel (Till)			15.3	25	5				5	clay with chalk gravel.			5							5							
					6				6		5.3	9		Sand and gravel			8.3	113	6	Sand and gravel	6.1	1010					
							(17) 5.2	(18-20) 18																			

Fig. 4.23

#### 4.4.3 Conclusions

The resistivity range of the fill material is 11 to 28 ohmm. The resistivity range of the underlying material, which is clay in BH 6F, is 9 to 25 ohmm. There is virtually no difference in the resistivity ranges of the two materials. The success in interpreting the depth of fill is therefore dependant on the two materials having resistivity values at the opposite ends of their ranges at the survey point. At positions 9E and 6F (without nominating layer thicknesses), this condition was not met, and the interpretation failed to identify the clay base. Sounding 9+10mE+20m produced an interpretation which gave a realistic depth of fill because there was sufficient contrast. The problem of lack of contrast between fill and host material was encountered by Knight et al (1978). The resistivity of the fill is also similar to that found by Knight et al.

The combination of resistivities and thicknesses which fit the field curve is too great to enable the interpretation procedures to be used without a borehole control. This any information which enables an estimation of the likely thickness should be used to construct the initial model, which would then limit the number of possible equivalent interpretations.

The sounding curves were not affected by "noise" to the extent that would have made interpretation impossible. Individual anomalous readings could be recognised in the field and further readings taken to give a more realistic

value thus providing a smooth curve. Repeated anomalous readings, which produce a deflection on the raw data sounding curve can be recognised during the interpretation stage and smoothed, when it becomes apparent that a realistic model cannot produce a curve which matches the field curve. The equipment and interpretation program used therefore provide opportunities for dealing with noisy results of the type which would be expected on fill.

The two curves obtained from soundings on the host material were interpreted realistically using the program. There is a suggestion from these interpretations that the sand and gravel thickness is less on the southern side of the site than on the western. This tends to support the assertion that the original deposit was wedge-shaped.

In summary, the method cannot be used on this or sites with similar base materials to detect the depth of fill without borehole control. It could be used for interpolation between boreholes. The degree of success to be expected from other types of landfill/host material combination is dependant on the nature of the host material and the groundwater conditions, as was pointed out for the resistivity traversing example.

#### 4.5 Apparent Resistivity Space Sections

(An alternative method of presenting and interpreting soundings)

##### 4.5.1 Method

Resistivity space sections can be compiled from lines of soundings which leads to an alternative method of interpretation. Values of apparent resistivity obtained from the sounding curves are plotted on the vertical axis at distances below a datum equivalent to the electrode spacing. A series of such values is plotted at distances along the horizontal axis equivalent to the station interval. The resistivity space beneath the datum is then contoured to reveal in a qualitative way the distribution of apparent resistivity of the ground.

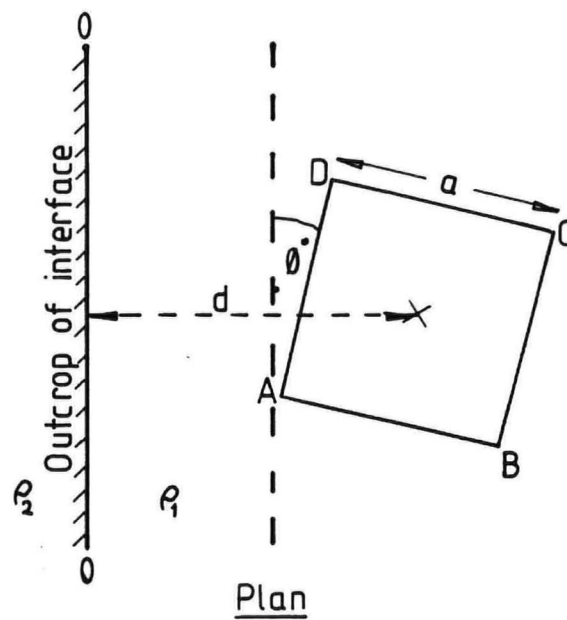
Three resistivity space sections were compiled from lines of soundings taken across the tip boundary at 5m and 10m intervals on lines X-X, 4 and 9. Their location is shown on Fig. 2.2.

Several electrode configurations were attempted for the individual soundings. Initially a square electrode array was used for Line X-X. This configuration is less sensitive to lateral variation of the ground than the colinear arrays, (Habberjam and Watkins, 1967) and has been used as the basis of an interpretation system employing resistivity space sections (Broadbent and Habberjam, 1971).

The field procedure required for soundings using the square array is slow. At best, four tapes are required fixed to the centre of the square and spreading diagonally to the corners. Each electrode has to be moved, for successive readings, a distance along the diagonal corresponding to 0.71 times the increment of 'a', which is the electrode separation measured along the sides of the square. Thus, a conversion table or calculator is required to provide whole number increments of 'a'. The nomenclature adopted for the square array is shown on Fig. 4.24.

In an attempt to overcome the cumbersome field procedure, on Line X-X a modification was tried which gave an approximate equivalent to a line of soundings. The soundings were compiled from a series of constant electrode separation traverses (profiles) across the boundary. Each traverse comprised readings taken at intervals of  $x$  with a square electrode configuration using one 'a' value for the whole traverse. Successive traverses were conducted using the same station positions and intervals of  $x$ , but with increasing 'a' values. Thus, in practice two traverses were laid out with two electrodes per line.

To speed up the procedure, one tape line was maintained throughout the survey so that one side of the electrode square followed the same line during successive traverses. This meant that for each increment of 'a', the centre of the soundings moved away from the fixed line by a distance equal to  $0.5a$ . The resistivity space section produced was not therefore, on a vertical plane.



Nomenclature used with square array  
over dipping interface (after Broadbent  $\propto$  Habberjam)

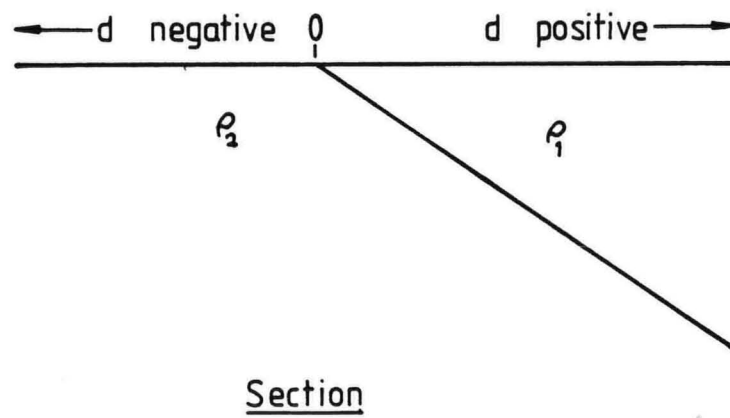


Fig. 4.24



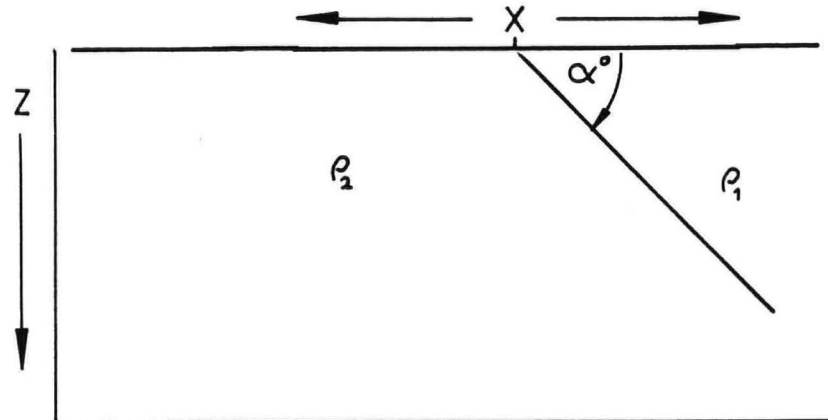
Lines 4 and 9 were surveyed using the Schlumberger electrode configuration with the array perpendicular to the traverse line (parallel to the strike of the boundary). Line 4 was surveyed across part of the tip/host material boundary where the traverses and the iso-resistivity contour plan showed little contrast and a shallow gradient. Line 9 was surveyed across the part of the north boundary typified by resistivity highs and large resistivity gradients.

#### 4.5.2 Interpretation Techniques

Techniques have been developed for interpretation simple resistivity space sections (Broadbent and Habberjam (op. cit.), and Habberjam and Jackson 1974). In particular, the distribution of apparent resistivity at a boundary for various values of dip angle has been examined by these authors. They have shown that the resistivity space displayed by iso-resistivity contours takes the form of a set of radiating contours originating from the point on the ground surface at the junction of the two materials. The value of resistivity changes uniformly in a direction perpendicular to the radiating contour lines, so that contours are equally spaced. The rate of change in resistivity across the boundary is a function of the dip angle and the resistivity contrast. This convergence pattern occurs with any electrode configuration. Fig. 4.25 from Broadbent and Habberjam (op. cit.) shows this convergence pattern.

# Apparent Resistivity across a dipping interface

## Geoelectric Section



(from Broadbent and Habberjam, 1971)  
Fig. 4.25

Broadbent and Habberjam describe a method of deriving the resistivity contrast ( $k$ ) and the dip angle ( $\alpha$ ) from families of master curves compiled by plotting the fractional change in apparent resistivity:

$$J = [(\rho_m - \rho_1) / (\rho_2 - \rho_1)]$$

against the angle made with the horizontal by the particular iso-resistivity contour ( $\beta$ ). They present a series of master curves which are polar diagrams of the locus of the variation of  $J$  with the angle  $\beta$  (the dip of the iso-resistivity contour in apparent resistivity space). Each locus is unique for each combination of interface dip angle ( $\alpha$ ) and resistivity contrast ( $k$ ). These curves have been worked out using the square electrode configuration and cannot be applied to resistivity sections derived from other electrode configurations.

This interpretation method presupposes a resistivity model consisting of two materials only, with no overburden. The ground at the site under investigation does not approximate to this model. There is a gravelly clay cap over fill on one side of the boundary, and in its simplest form, sand and gravel over clay on the other side of the boundary.

Habberjam and Jackson (1974) have shown that, in the same way that real resistivity space can be combined by simple mathematical operations to give complex models, simple apparent resistivity space can be combined to form a complex apparent resistivity space. The reverse process of

obtaining a simple apparent resistivity space from a complex space can also be achieved, from which an interpretation using the methods outlined in Broadbent and Habberjam (1971) can proceed.

#### 4.5.3 Presentation and Discussion of Results

Fig. 4.26 shows the contoured apparent resistivity space section compiled from square array soundings on Line X-X obtained by superimposing traverses. Comparison with the theoretical contour pattern over a boundary shown on Fig. 4.25, shows some similarities. There is a convergence of iso-resistivity contours towards a horizontal pattern of close spaced contours, west of the interface, which is indicative of the dipping interface model with overburden. In addition to this pattern, there is an additional convergence feature at values of 'a' less than 5m, centred at 9m on the fill side of the boundary. Unfortunately, this feature is insufficient to allow a qualitative interpretation, using the method of Broadbent and Habberjam (1971).

The impression given by the section is one of a high resistivity host material ( $> 200$  ohm) at shallow depth underlain by low resistivity material (32 ohm) which is underlain by an increasingly higher resistivity material. In crude terms, this conforms to the known soil at this position, being dry sand and gravel, over clay over sand and gravel. The contours on the fill material show a low apparent resistivity at shallow depth (8 ohm metres)

Apparent Resistivity Space Section - Line X-X  
Square Array

Feb.-March 1982

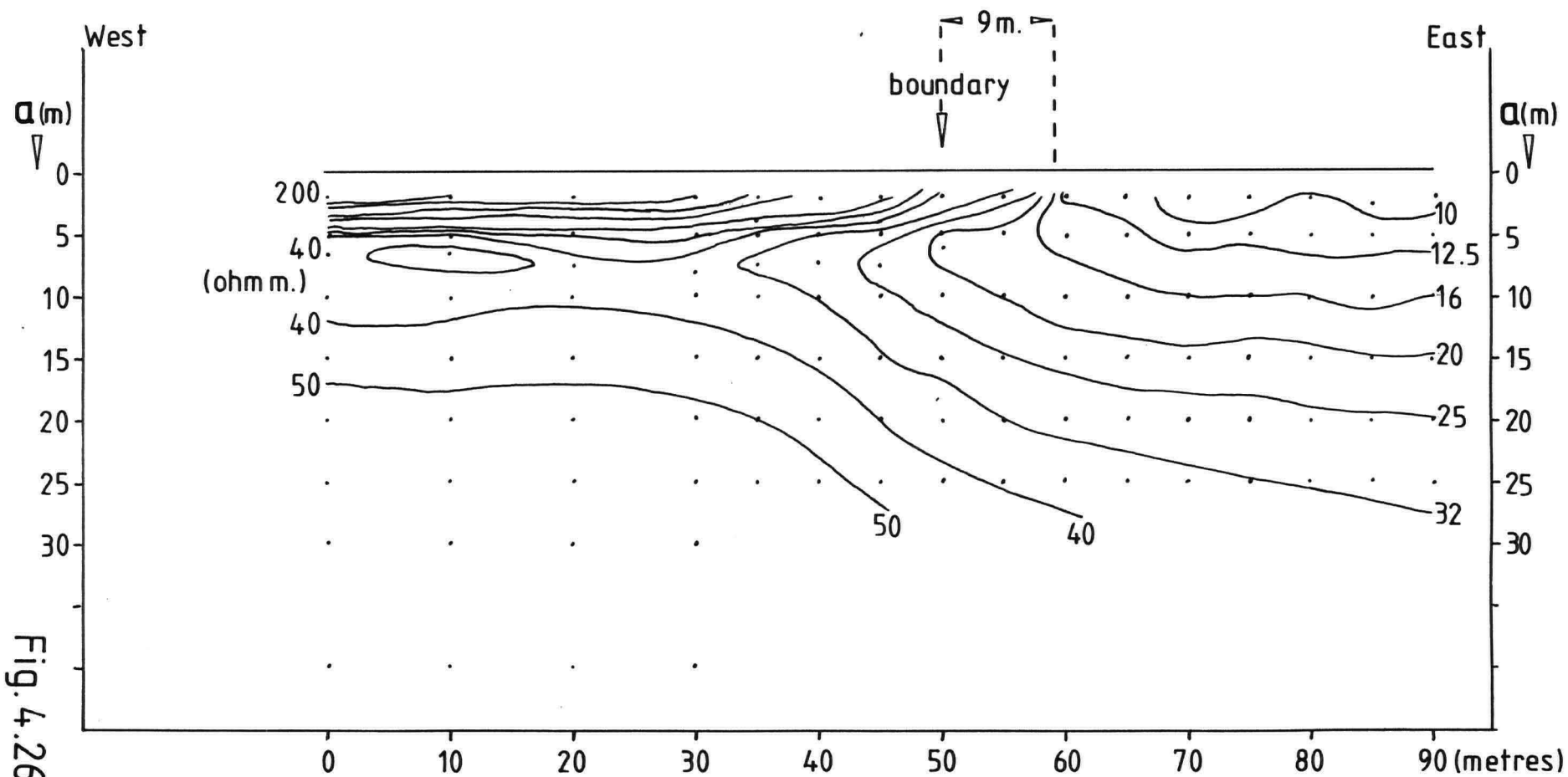


Fig. 4.26

increasing to 40 ohm metres at an electrode spacing of 25m. There is no indication of high resistivity at very small values of 'a', but this is a limitation of the scale at which the 'a' values were plotted.

Fig. 4.27 shows the apparent resistivity section compiled from Schlumberger soundings on Line 4. The contour pattern for electrode separation values (L) of less than 10m shows some indication of a converging pattern. There is an extension of higher resistivity over the fill material which may represent the clay cap.

There is a shallow resistivity "high" to the south of the boundary with resistivity values of 200-260 ohmm. These values are similar to those obtained in the Schlumberger sounding at 2F, which are known to be produced by sand and gravel. The resistivity values below this "high" are similar to those known to be produced by chalky boulder clay. The section therefore suggests a sand and gravel lens (resistivity 200 ohmm) resting on till (resistivity 20-30 ohmm). This is further evidence suggesting that the sand and gravel thins out on the southern boundary, as discussed in Chapter 2.

The topographic expression of the boundary on the southern side of the landfill is not distinct, therefore the position of the boundary indicated on Fig. 4.27 is approximate. However, it shows a general agreement with the apparent resistivity space, as it coincides with the point at which the contours tend to converge at grid Line H. The accuracy

# Apparent Resistivity Space Section (Schlumberger)

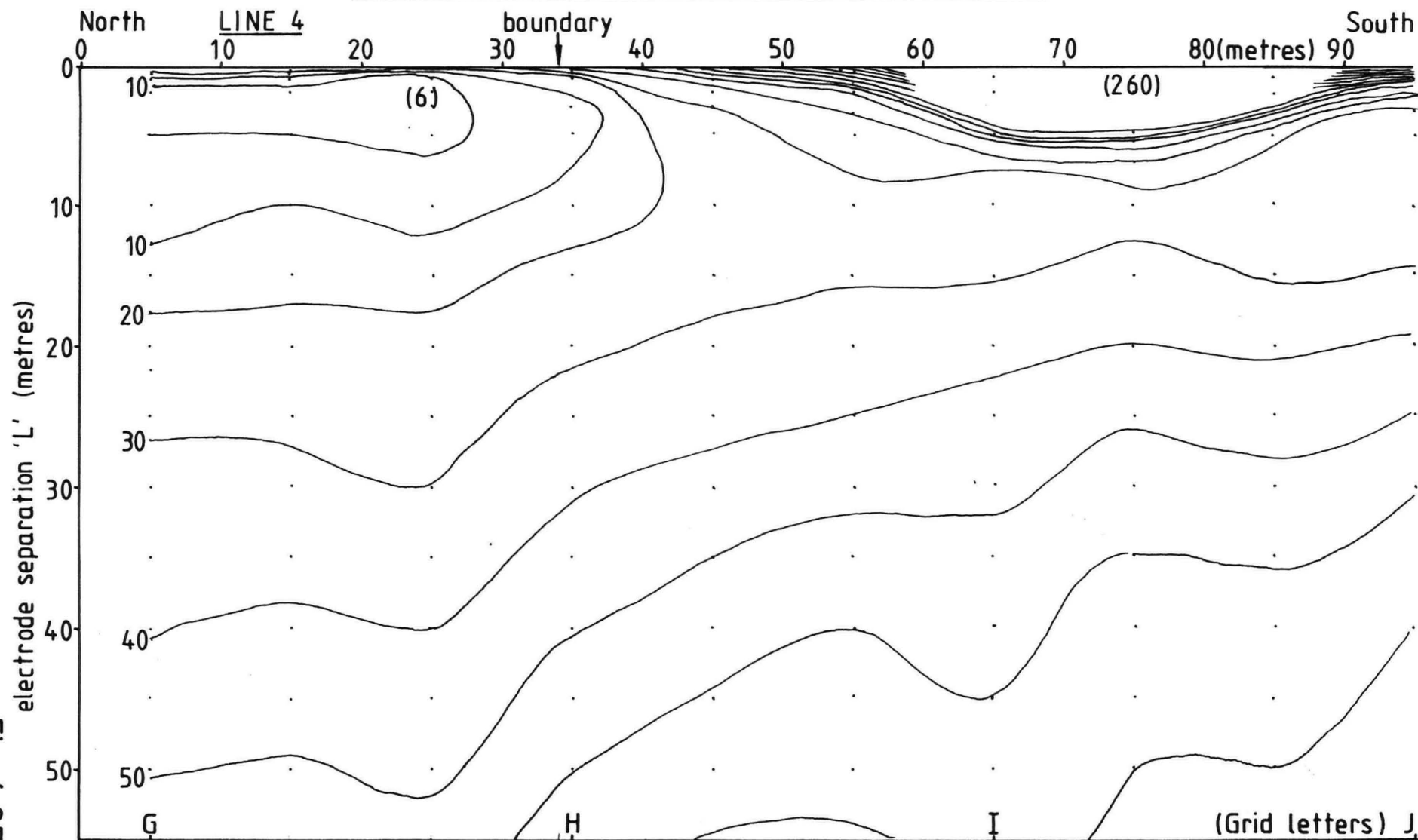


Fig. 4.27

of the location of the boundary using the point of convergence is no better than  $\pm 5\text{m}$ .

Fig. 4.28 shows the apparent resistivity section on Line 9 across the northern fill/host material boundary. The immediately noticeable feature of this section is the anomalously low resistivity recorded at sounding 9D. It is suggested that this has been produced by metal at shallow depth. This feature will be discussed in relation to other traverses across this point in the section on comparison of methods.

The section otherwise shows a high resistivity material,  $>200\text{ ohmm}$ , at shallow depth to the north of the boundary. The resistivity in this region exceeds that found elsewhere on the site; values of  $1900\text{ ohmm}$  are recorded. The high resistivity space does not clearly extend across the boundary at shallow depth, as it does on Line 4. However, this is partly because there is less contrast on the fill side of the boundary between the near surface resistivity values and the material beneath. The reduced contrast results from an increased value of resistivity of the lower material which is generally  $20\text{ ohmm}$ . On Line 4 the equivalent space has a value of  $10\text{ ohmm}$ .

The topographic expression of the boundary is approximately  $5\text{m}$  north of the point at which the resistivity space at shallow depth changes abruptly. The resistivity space changes at 'L' values of  $10\text{m}$  to  $50\text{m}$  in a horizontal direction in a zone approximately  $20\text{m}$  north of the boundary.



# Apparent Resistivity Space Section (Schlumberger)

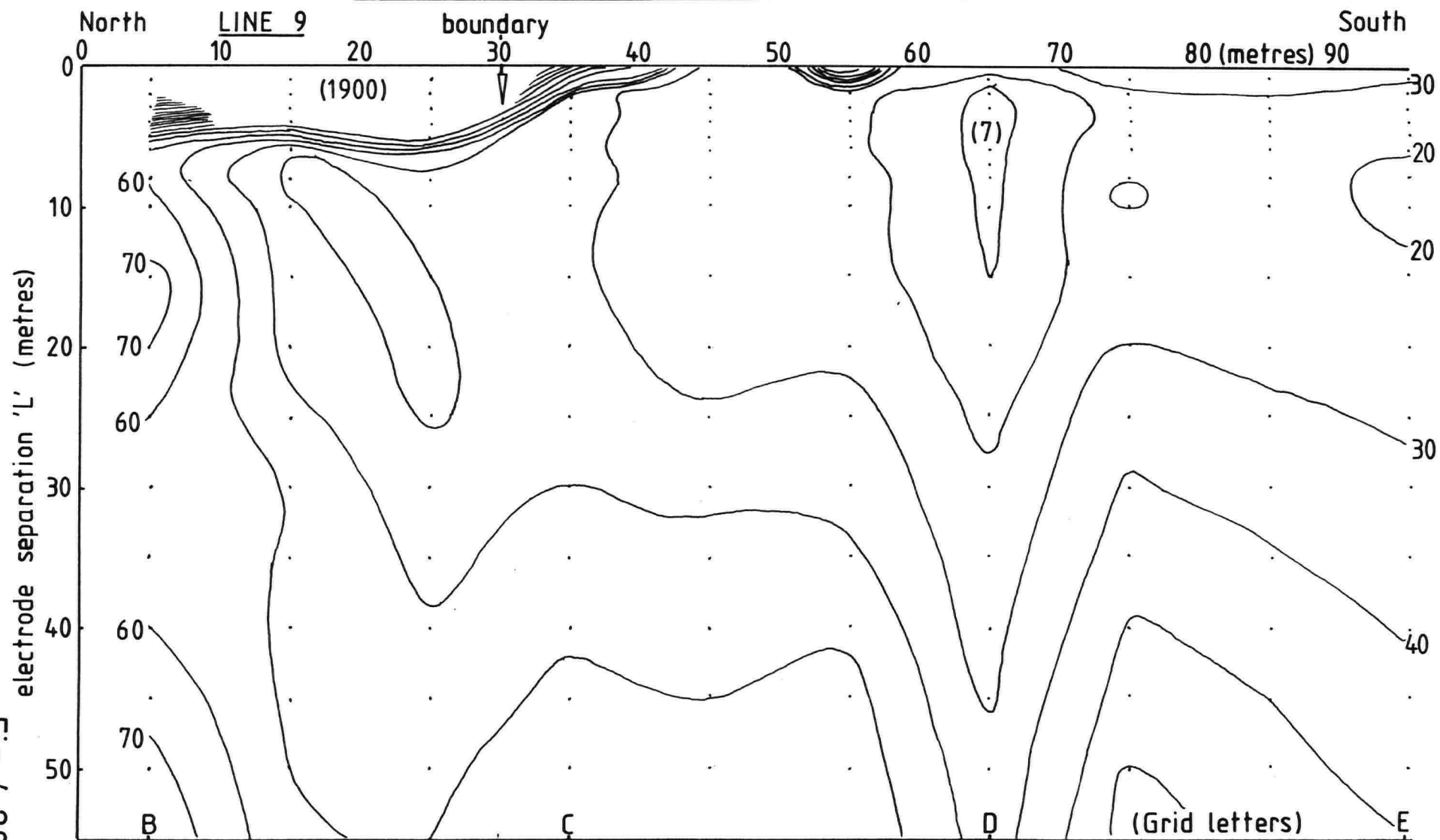


Fig. 4.28

There is no suggestion of a radiating contour pattern on this section. There is an extension of low resistivity space, from the fill area northwards across the boundary and beneath the high resistivity material. This may represent a leachate plume.

The section generally is complex compared to those on Line 4 and Line X-X. Even if the effect of sounding 9D is ignored, the resistivity space shows an abrupt change, but this change is not coincident with the boundary.

#### 4.5.3 Conclusion

The apparent resistivity space sections constructed for lines X-X and 4 reveal the radiating contour pattern, at small electrode spacings, typical of a dipping interface. The pattern departs from simple convergent contours at large values of electrode separation. This is to be expected as the dipping interface only pertains over a limited depth range.

The convergent pattern gives an indication of the position of the outcrop of the dipping interface, but on line X-X the predicted position is 9m beyond the surface expression of the boundary on the host side of the host/fill boundary. A section derived from more closely spaced soundings and at shallow depths may have provided a more accurate indication of the boundary position.

A general impression of the distribution of ground resistivity can be obtained from an examination of apparent resistivity distribution. Quantitative analysis using the method of Habberjam et al (op. cit.) is not possible on this site, where the actual ground configuration does not match the simple model required in the interpretation. The contour pattern on Line 4 suggests a thinning of the gravel to the south of the site.

The compilation of resistivity space sections, from soundings using the square array electrode configuration, is cumbersome and slow to use in the field. It can be made

easier by compiling a series of traverses with a common station interval and successively greater 'a' values. If quantitative interpretation is not required, it is quicker to use Schlumberger soundings to compile the section.

## 5.1

A Review of Similar Applications

There have been many papers published within the last six years describing the use of the Geonics EM31, in particular, in the detection and mapping of leachate plumes in the vicinity of landfill sites, for example, Slaine and Greenhouse (1982), McNeill (1982). The higher conductivity of water contaminated with salt has also enabled areas of salt water to be mapped (De Jong et. al. 1979, Cameron et. al. 1981 and Stewart 1982). The principal of mapping conductive ground water had been proven with resistivity techniques (Cartwright and McComas 1968). The use of the EM31 is an extension of the technique.

Most papers have reported on comparative trials between conventional resistivity traversing and traversing using the EM31. A common conclusion is that the continuous readings provided by the EM31 make the acquisition of detailed information quicker than the conventional resistivity techniques.

Stewart (1982) concluded that the method is best suited to shallow depths and that it was useful as a monitoring technique because the method does not provide qualitative information except over the simplest geological structures. Ladwig (1983) suggested that it should be used in conjunction with conventional resistivity techniques. This

would then compensate for the lack of depth control information possible with the EM31.

All of the above accounts illustrate the use of the instrument to traverse the survey area and provide conductivity profiles from which contoured plans were derived. Few results from using the EM31 as a sounding device have been reported.

A potential limitation of the application of the E.M. method was demonstrated by Glaccum et. al. (1983). They were aware that the E.M. readings depart from a linear relationship with high ground conductivities. They claimed to have demonstrated this effect by comparing the results from E.M. traverse and conventional Wenner resistivity traverses converted to units of conductivity.

They produced a profile using an EM31, with an effective survey depth of 6m, which showed lower peaks on the conductivity profile than a Wenner traverse with an 'a' spacing of 6m. They applied a correction to the E.M. data using the manufacturer's correction curve and found close agreement with the Wenner resistivity traverse. (They acknowledged that the correction curve assumes an homogenous half-space, which the ground they were surveying was not).

They also compared the results from an EM34-3 conductivity traverse with an effective survey depth of 15m, with a Wenner resistivity traverse with an 'a' spacing of 15m. They found the differences more marked than on the previous

survey. They claimed that the very high conductivity produced a reduction in E.M. readings. They defined the value of conductivity above which readings began to decrease as 62 mmhos/m (16 ohmm).

It is also reasonable to assume that the method would suffer the same disadvantage as resistivity traversing of being unable to detect the physical boundary of a landfill where leachate is permeating into the host material, as a result of the masking effect of the leachate.

## 5.2 The Equipment and Measurement Characteristics

The instrument used was the Geonics EM31. It is one of the fixed coil types of electromagnetic surveying instruments with an intercoil spacing of 3.66 m and produces a time varying magnetic field from a 9.8 kHz alternating current. In the normal position the dipoles are vertical. This equipment has the intercoil spacing and the frequency of the alternating current adjusted to produce a secondary field which is linearly proportional to the terrain conductivity for values of conductivity below about 100 mmhos/m (McNeill 1980). The important characteristic of this arrangement is that current flow induced in any particular layer of ground is unaffected by current in other parts of the ground. Therefore, the relative response of layers of successively increasing depths is predictable. This enables the changes in the measured apparent conductivity to be attributed to changes in thickness of a particular target layer, provided that the conductivities and the thickness of the layers are known, or can be assumed.

A quantity known as the cumulative response  $R(z)$  has been defined by McNeill (1980) for dipoles vertical and horizontal, as follows:

$$\text{Vertical Dipoles} \quad R_v(z) = \frac{1}{(4z^2 + 1)^{\frac{1}{2}}}$$

$$\text{Horizontal Dipoles} \quad R_h(z) = (4z^2 + 1)^{\frac{1}{2}} - 2z$$



where  $z$  is the depth divided by the intercoil spacing. It defines the contribution of layers at various depths to the measured apparent conductivity.

If the ground profile is unknown, some information can be obtained from the instrument by taking two readings at each survey point, one with the dipoles vertical and one with the dipoles horizontal. Because the response relative to depth relationship  $[R(z)]$  is different for the two dipole orientations, a two-layered earth can be identified together with an indication of whether the conductivity is increasing or decreasing with depth.

The operating manual provides a curve showing the variation in the cumulative response of material below successive depths down to a depth equal to twice the intercoil spacing (7.32m). Using this relationship, it is possible to calculate the apparent conductivity measured by the instrument from the formula:

$$\sigma_n = \sigma_1 [1 - Rz_1 + K_2 (Rz_1 - Rz_2) + K_{n+1}Rz_n]$$

In the normal operating position, the effective survey depth is 6 metres with 50% of the instrument's response coming from material between ground level and 2.75 metres (Fig. 4 EM31 Operating Manual). The instrument is not capable of measuring conductivity below 1 mmho/m (greater than 1000 ohmm). Above 20 mmhos/m (below 50 ohmm), the response begins to depart from a linear relationship. The manual suggests that the response is sufficiently linear up to 500

mmhos/m (down to 2 ohmm). Glaccum et al (1983) found that generally conductivities above 50 mmhos/m (below 20 ohmm) caused departure from linearity.

### 5.3 E.M. Traversing

#### 5.3.1 Method

Conductivity readings were taken along the same traverse lines as were used for the resistivity survey at 5 metre intervals, or more frequently where the gradient of conductivity increased. Thus, generally the ground was sampled at regular intervals but, where necessary, continuous readings were obtained and the positions of maxima and minima noted.

A short series of closely spaced, short traverses were also surveyed on grid lines A+10 to C+10 from grid lines 8 to 11. This area was of interest because the resistivity traverses showed large resistivity gradients.

All traverse readings were taken with the instrument at waist height (approximately 0.9m from ground level) and the dipoles vertical (the normal operating position). Two readings were taken at each station by rotating the instrument through  $90^\circ$  about the vertical axis. This provided a check on the homogeneity of the ground. (Trial and error showed that the greatest variation was exhibited by rotating the instrument through  $90^\circ$ , as would be expected, rather than  $180^\circ$ , and this is the procedure is recommended in the operating manual.) Both readings are plotted on the profiles and are joined by a solid vertical line, the length of which indicated the degree of lateral variation in the ground. The curve is plotted using the average of the two

readings. It is acknowledged that this average does not reflect the true ground conductivity when the difference between the two readings is large.

Trials were also performed with the object of determining the susceptibility of the instrument's orientation about the vertical axis. They consisted of readings of maximum and minimum conductivity noted during a revolution through 360°. The procedure was repeated at stations at 5 metre intervals on two sections on line 8 across the tip boundaries.

All results are presented as resistivity values. No attempt has been made to correct for the non-linearity of readings at high conductivities using the correction curve in the manual. This correction is minimal for the range of conductivity usually found on this site. For example, when the indicated conductivity is 100 mmhos/m, the corrected conductivity is 120 mmhos/m. In terms of resistivity these values are 10 ohmm and 8.3 ohmm respectively, a difference of 1.7 ohmm, which does not show on the scale to which the traverses are plotted.

### 5.3.2 Presentation of Results

The individual traverses are shown on Figs. 5.1 to 5.8. Table 2 contains a comparison of the conductivity readings (converted to resistivity values) of the host material and fill material. An indication of the variation of resistivity obtained is given by the Sample Standard Deviation. The contrast between the values of resistivity of the host and fill material is also included and expressed as a ratio. The values used in these computations exclude those erratic results from near the boundary. The part of the profile which was assumed to have been influenced by the boundary was decided by inspection, which inevitably introduces a degree of subjectivity.

The contrast in resistivity between the fill and host material is generally between 1:3 and 1:5. The variation as expressed by the Sample Standard Deviation is in the range of 2 to 5 on both the fill and host material, with the exception of a large variation on traverses 4,6, and 8 over the host material. Inspection of the relevant parts of these traverses shows that this variation can be attributed to anomalies near the host/fill boundary. Otherwise it is apparent that the variation in resistivity of the host material is less than that of the fill.

The gradient of the E.M. profile at the boundary has been calculated and included in Table 2. The values give the rate of change of resistivity per metre of traverse. The width of the profile over which there is a change in

resistivity is also included. This is open to subjective interpretation in most cases. The widths are quoted to the nearest 5m and vary from 10 to 80m.

The gradient of the profile across the boundary varies from 0.7 ohmm/m to 3.6 ohmm/m. It is possible that this reflects variations in the dip of the host/fill interface, but this cannot be established without excavation. The differences could also be caused by variations in the degree of leachate infiltration into the host material, or by lithological variation. The gradients do not suggest a steeper dip on the north boundary than the south boundary as was the case with the resistivity traverses.

All traverses which cross the north boundary, with the exception of No. 4, show high resistivity peaks in the region of the boundary. Lines 6 and 8 show a similar feature on the southern boundary. Lines E and G show a trough in the vicinity of the western boundary. These features are accompanied by larger than usual variations in the two readings obtained by rotating the instrument about the vertical axis through 90°. (This is shown on the profiles by the increased length of the vertical line, representing the difference between the two readings, in comparison to other readings on the profile). The peaks (or troughs in conductivity) are centred very close to the assumed boundary position, in most cases within 5m.

West LINE C EM 31 Traverse 4 November 1984 East

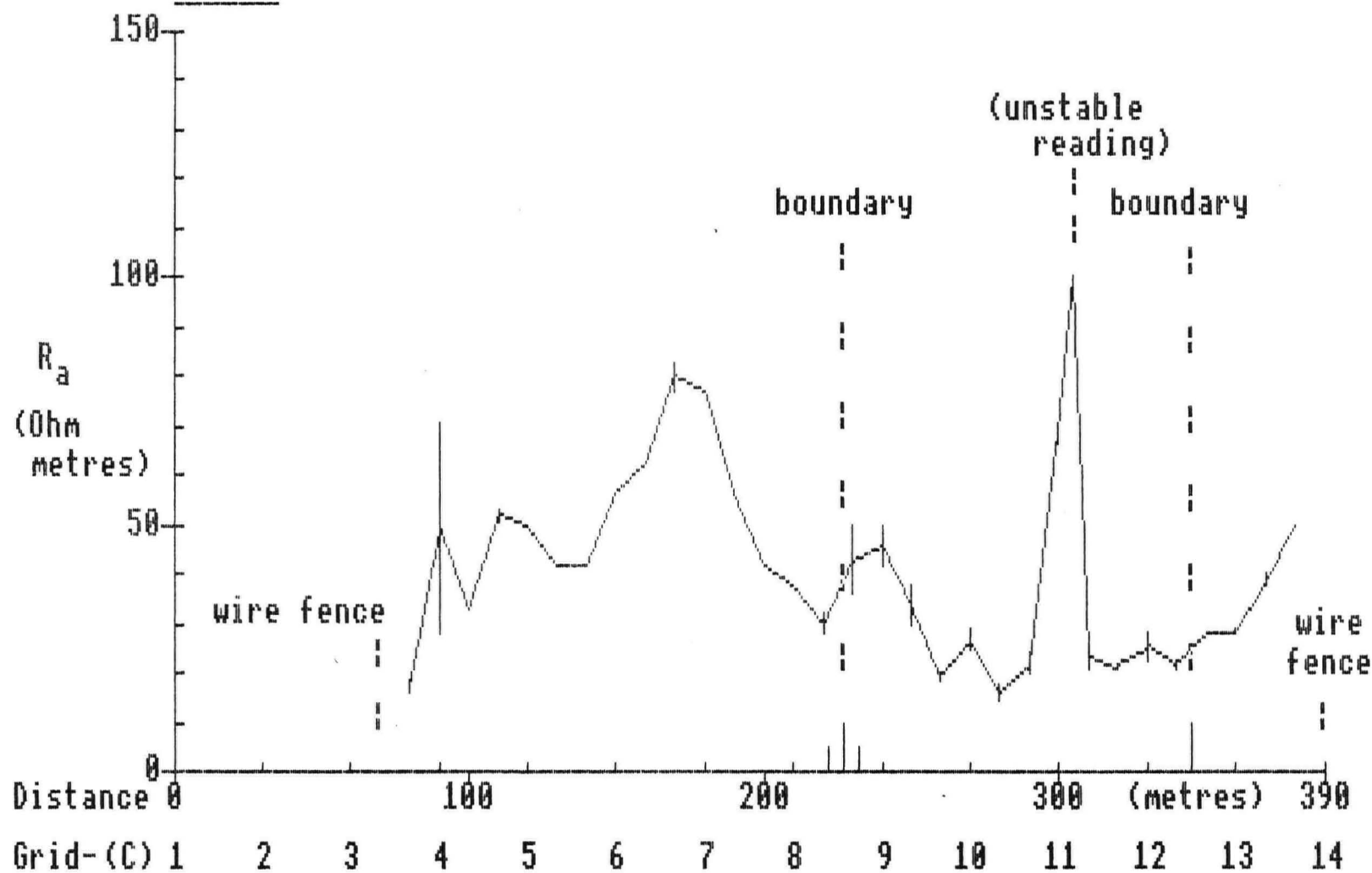


Fig. 5.1

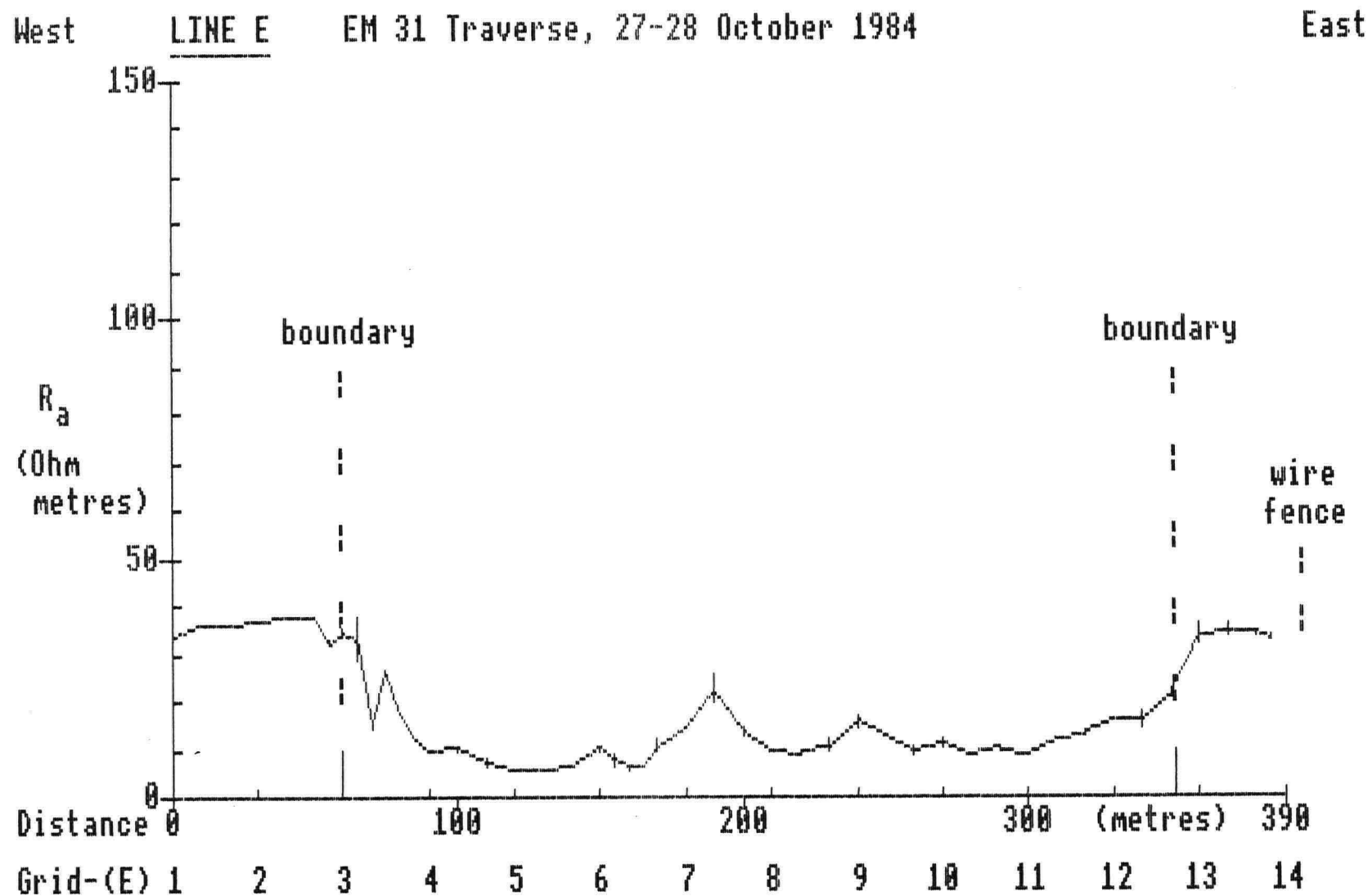


Fig. 5.2



West      LINE G      EM 31 Traverse, 2 November 1984      East

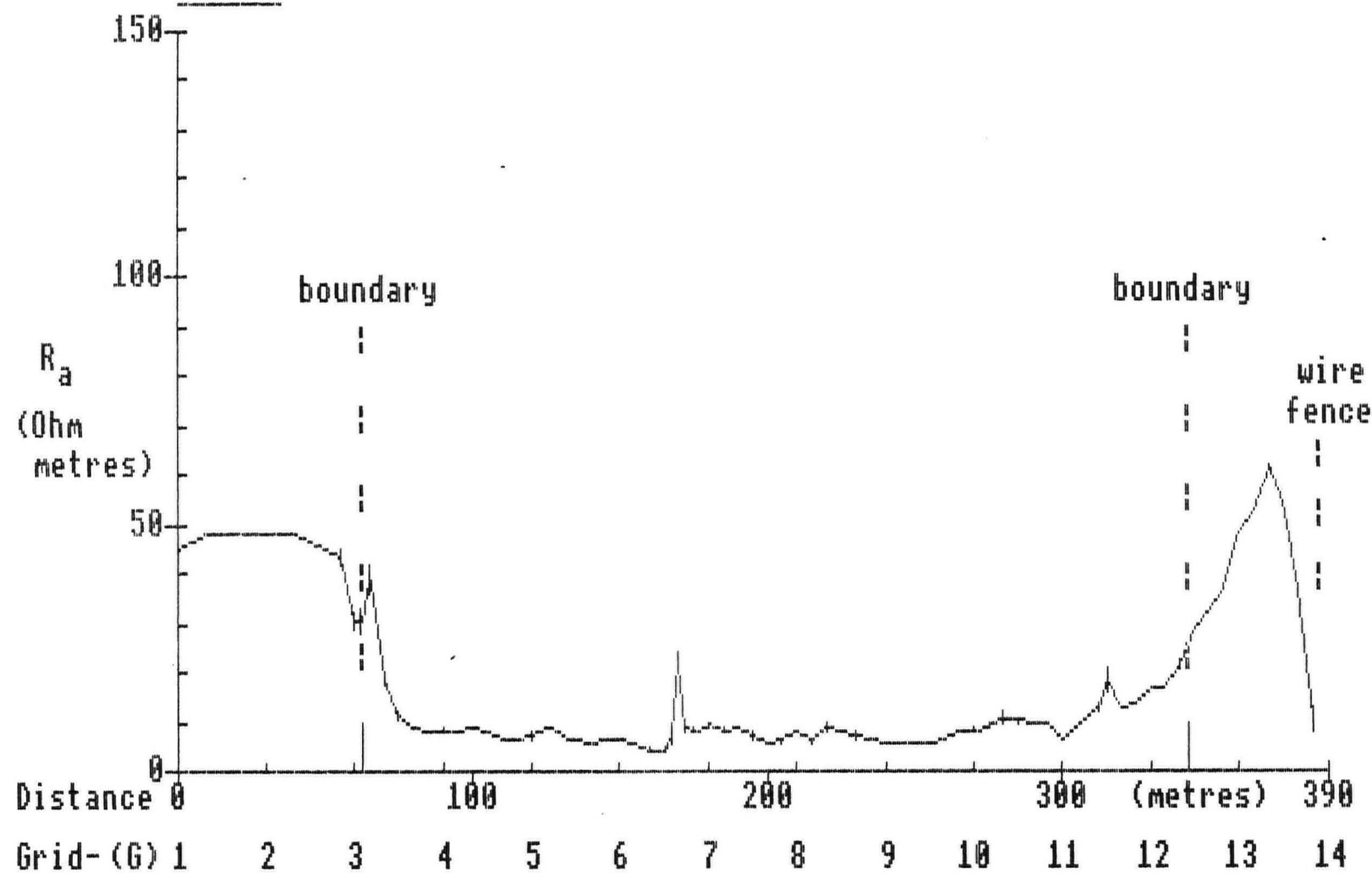


Fig.5.3

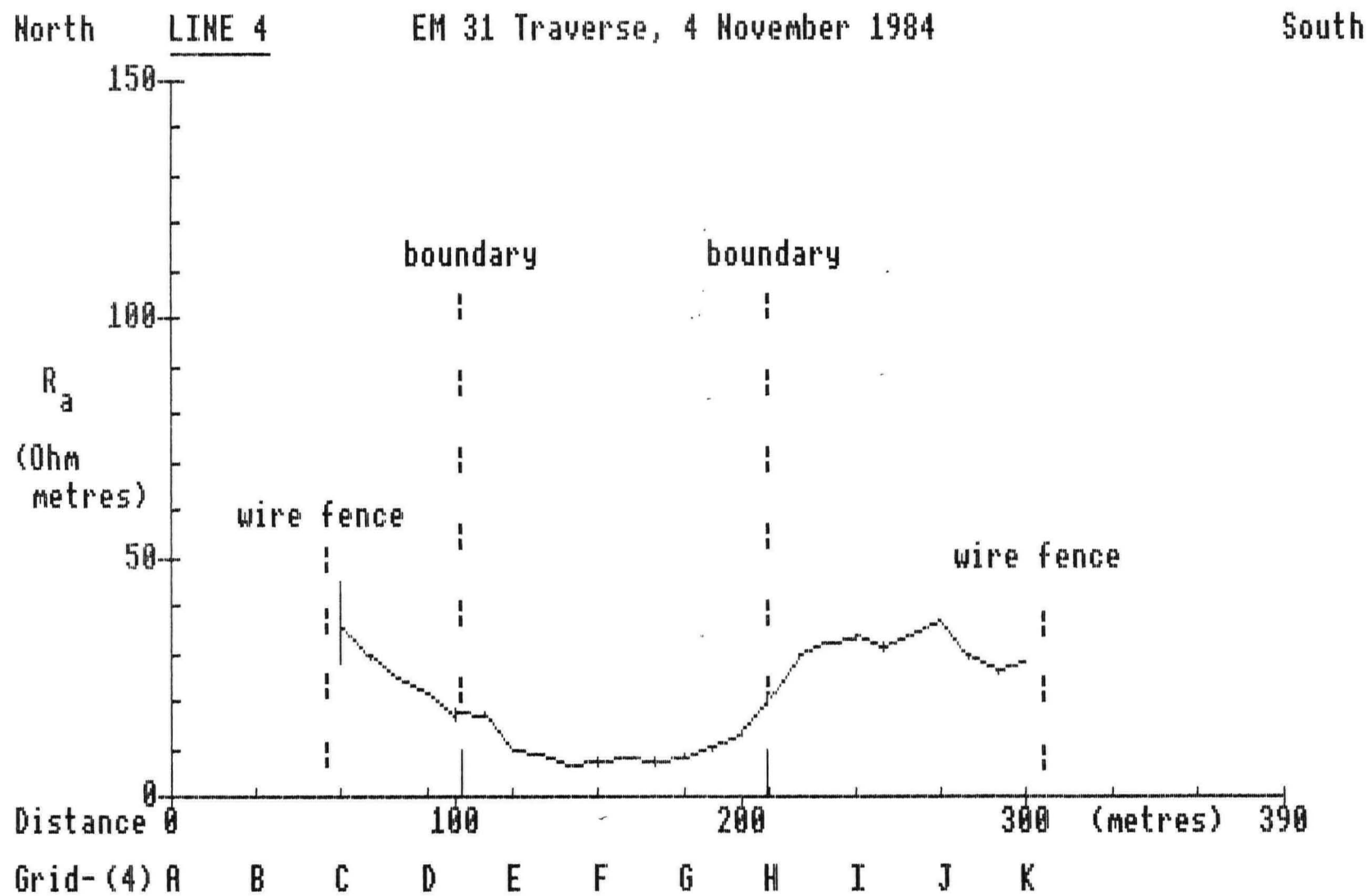


Fig. 5.4

North      LINE 6      EM 31 Traverse, 28 October 1984      South

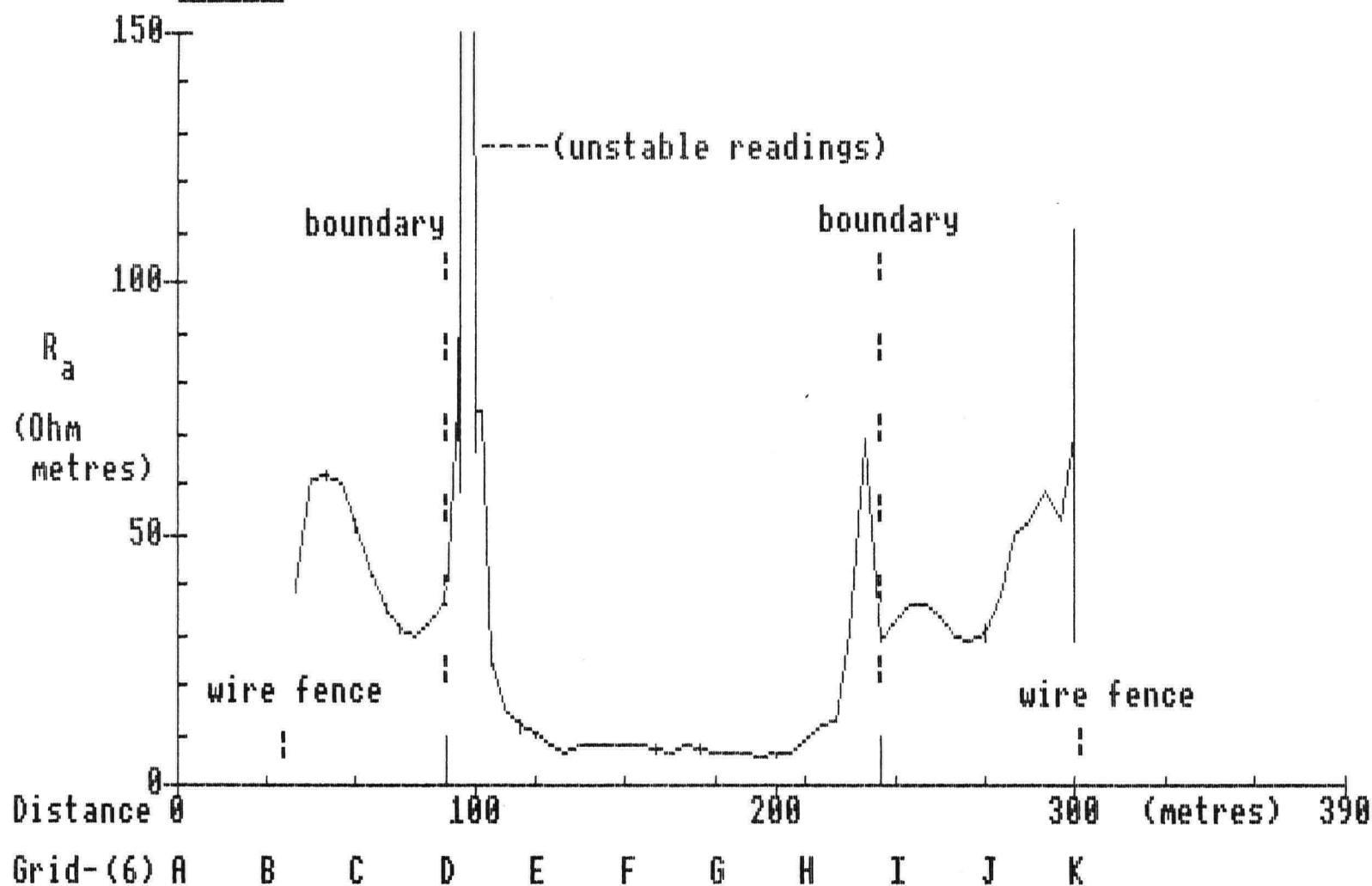


Fig.5.5

North LINE 8 EM 31 Traverse, 28 October 1984 South

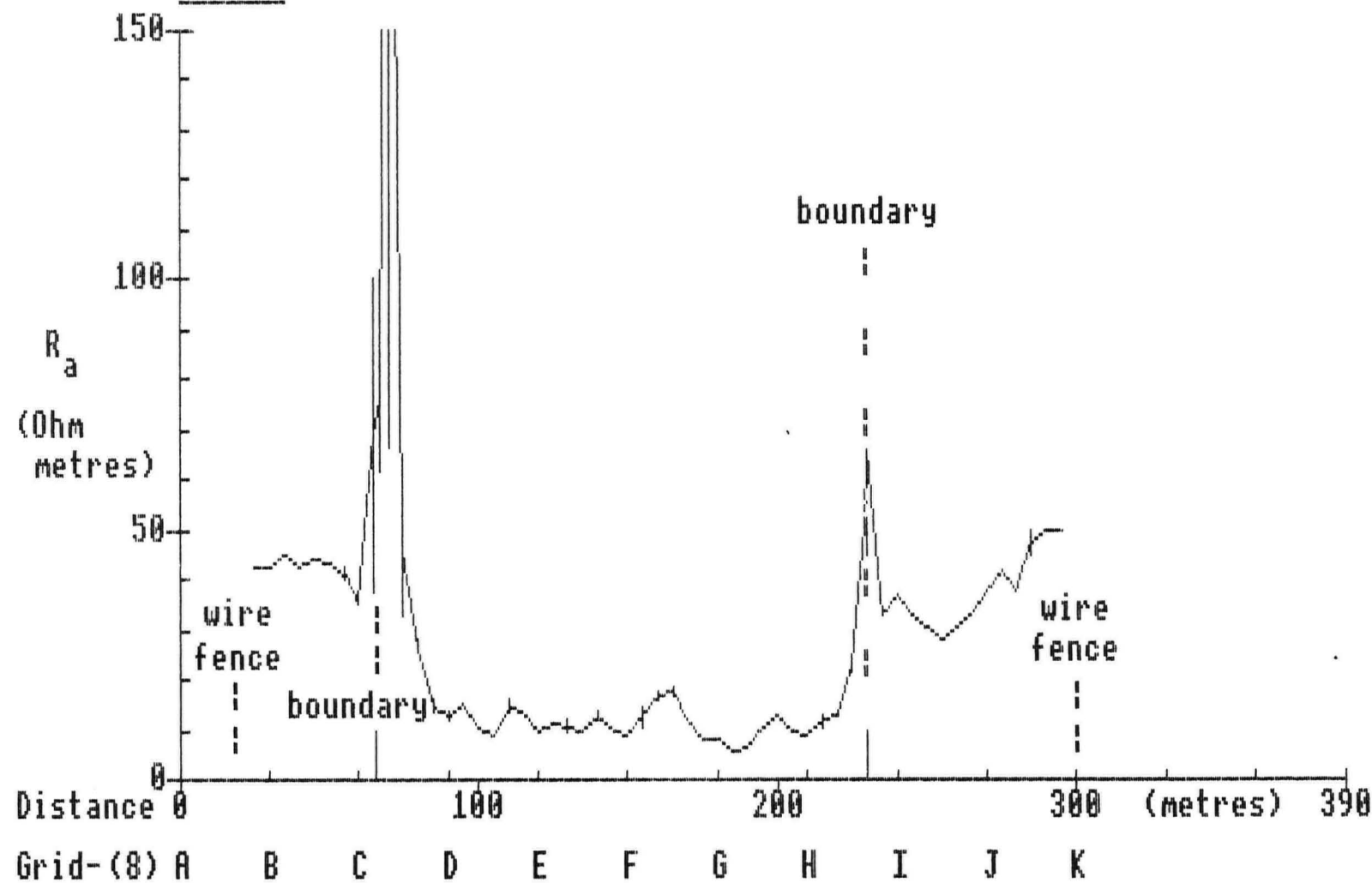


Fig. 5.6

North LINE 9 EM 31 Traverse, 2 November 1984 South

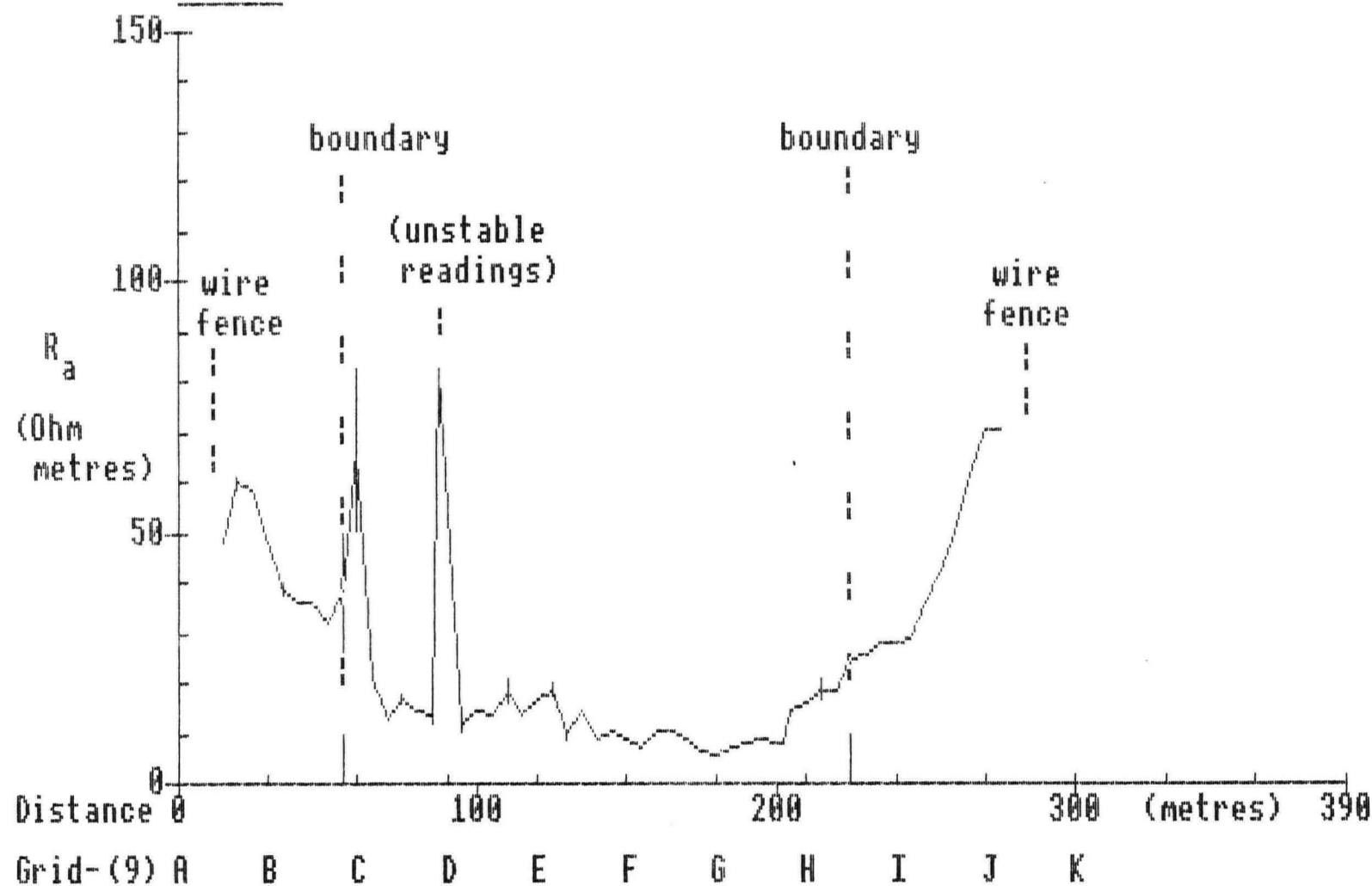


Fig.5.7

North LINE 11

EM 31 Traverse, 28 October 1984

South

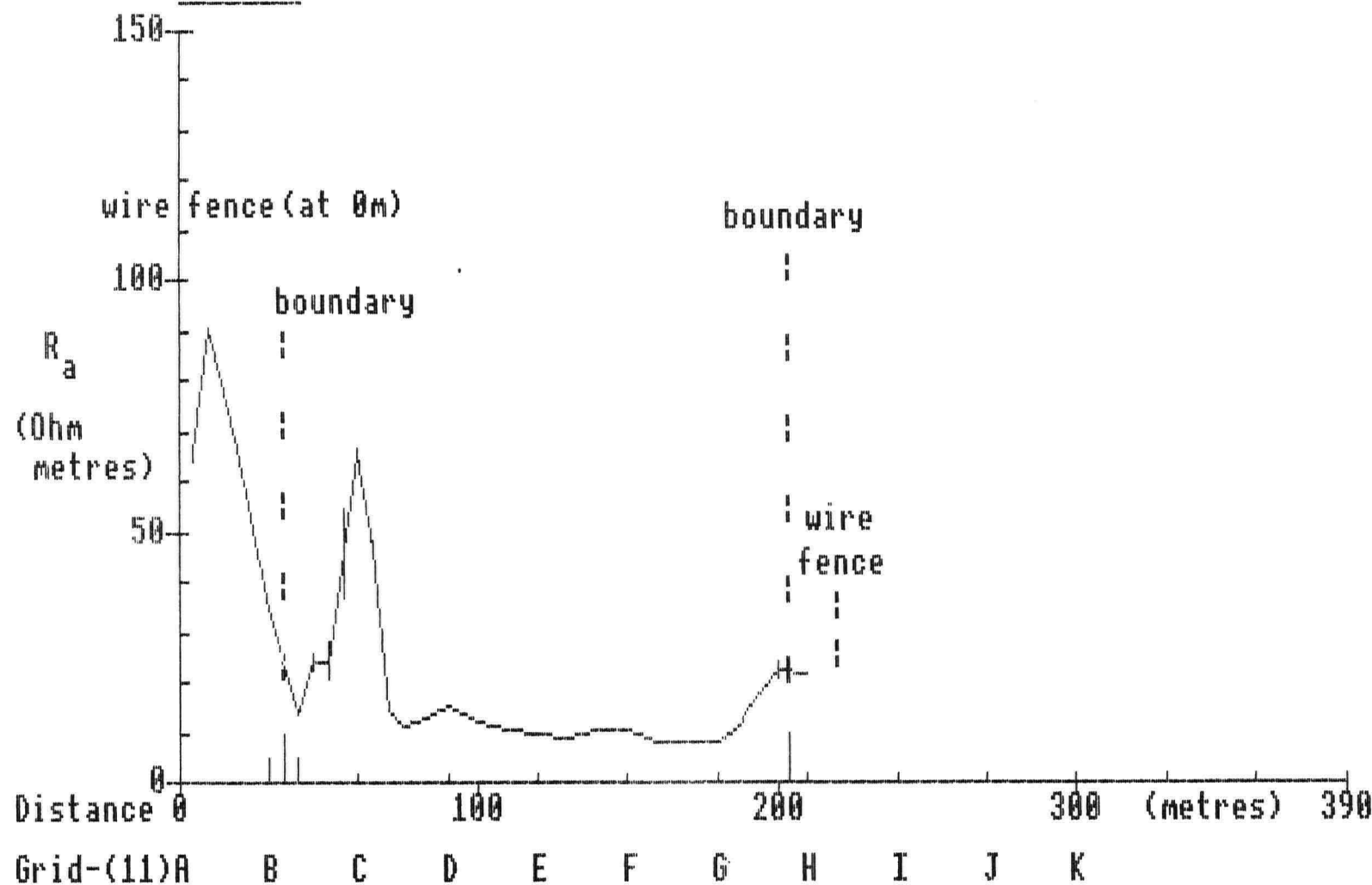


Fig. 5.8

TABLE 2

EM31 TRAVERSES

Traverse No.	HOST Resistivity n-1		FILL Resistivity n-1		Contrast	BOUNDARY Gradient		PROFILE Width (m)		Remarks
						N/W	S/E	N/W	S/E	
4 (N-S)	32	3.3	9	2.0	3.6:1	0.9	0.8	30	20	Profile oblique to boundary
6 (N-S)	60	80	8	2	7.5:1	0.8	3.6	80	5/60	Southern boundary ambiguous
8 (N-S)	41	11	12	3	3.4:1	0.8	1.2	40	20	Peak on north boundary
9 (N-S)	-	-	12	4	-	0.9	0.7	50	70	Peaks on N. boundary
11 (N-S)	-	-	11	3	-	-	0.8	-	20	Peaks on N. boundary
C (E-W)	-	-	-	-	-	-	-	-	-	Profile oblique to boundaries (erratic)
E (E-W)	34	4	12	5	2.8:1	1.2	1.2	20	10	Trough on west boundary
G (E-W)	47	2	9	3	5.2:1	1.2	1.1	15	40	Trough on west boundary

### The profiles across the fill/host boundary

The high resistivity peaked anomalies were investigated further. Broadside traverses (i.e. coils parallel to the strike of the boundary) were run across the southern boundary on Line 6 (Fig. 5.9) and across the northern boundary on Line 10 (Fig. 5.10). Line 10 had not been surveyed previously with the EM31, but adjacent Lines 8,9 and 11 had, and all showed peaks at the north boundary. Broadside traverses were run because they produce a simpler profile.

The survey method on these two traverses was altered from the fixed station interval method to a variable station interval which was dependent on the gradient of apparent resistivity. Thus it was intended to define more accurately the shape of the anomalies on the resistivity profile.

The profiles are reproduced on Figs. 5.9 and 5.10. They are plotted in units of conductivity and resistivity and have been manually smoothed between points. The conductivity profiles show asymmetric peaks flanking a trough, which is typical of the response produced by a dipping sheet conductor. The possible causes of this anomaly will be discussed in the interpretation section.

The northern boundary between Lines 8, 9, 10 and 11 was examined in more detail using close traverses from which a contoured resistivity plan based on a 10m grid was produced. This is reproduced on Fig. 5.11. The values plotted are averaged from the two sets of readings taken at 90° to each



LINE 6 (part)

EM 31 Traverse

16 June 1985

Variable station interval – broadside array.

Conductivity  $\times$  —————  $\times$

Resistivity  $\times$  —————  $\times$

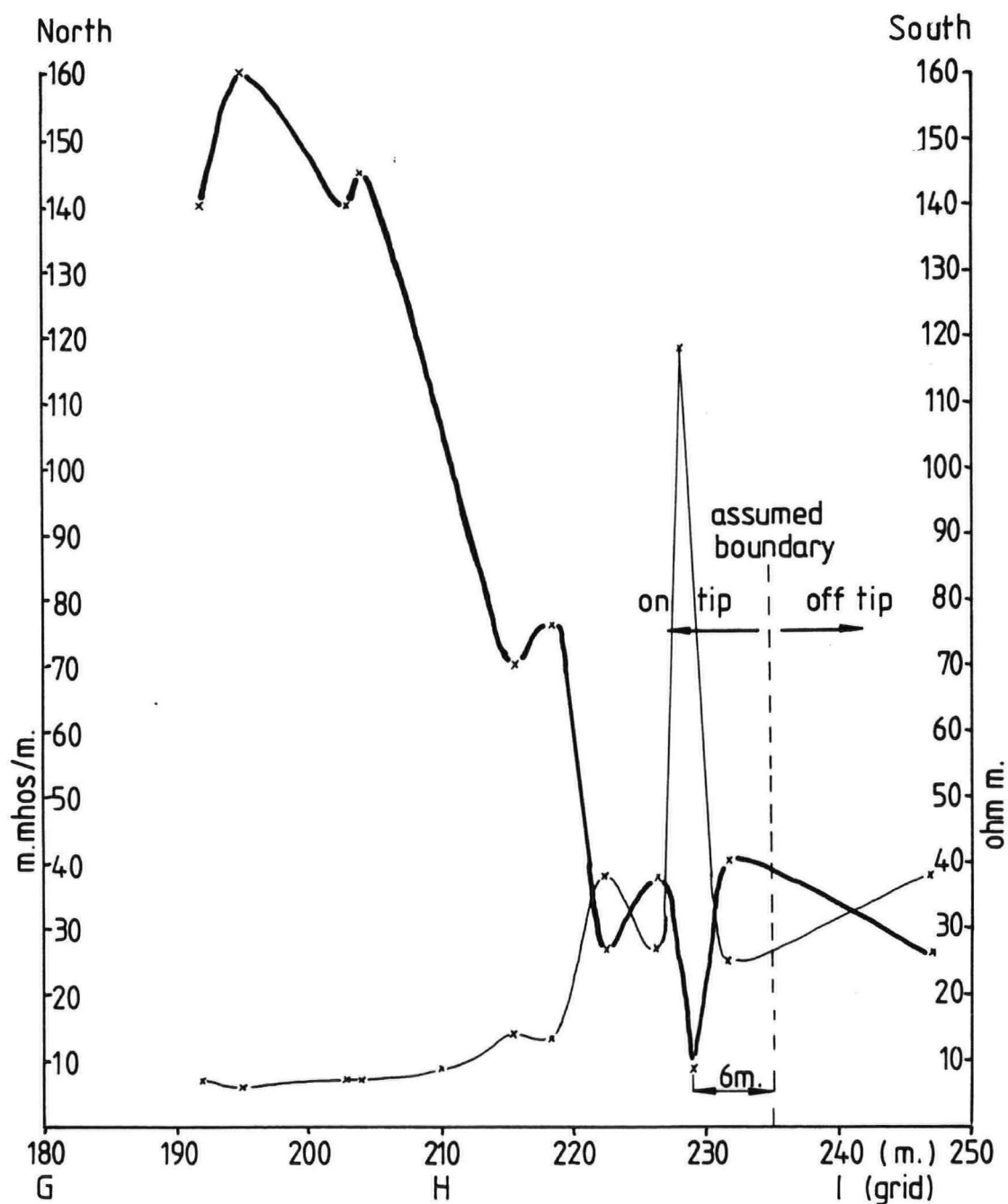


Fig. 5.9

Variable station interval — broadside array.

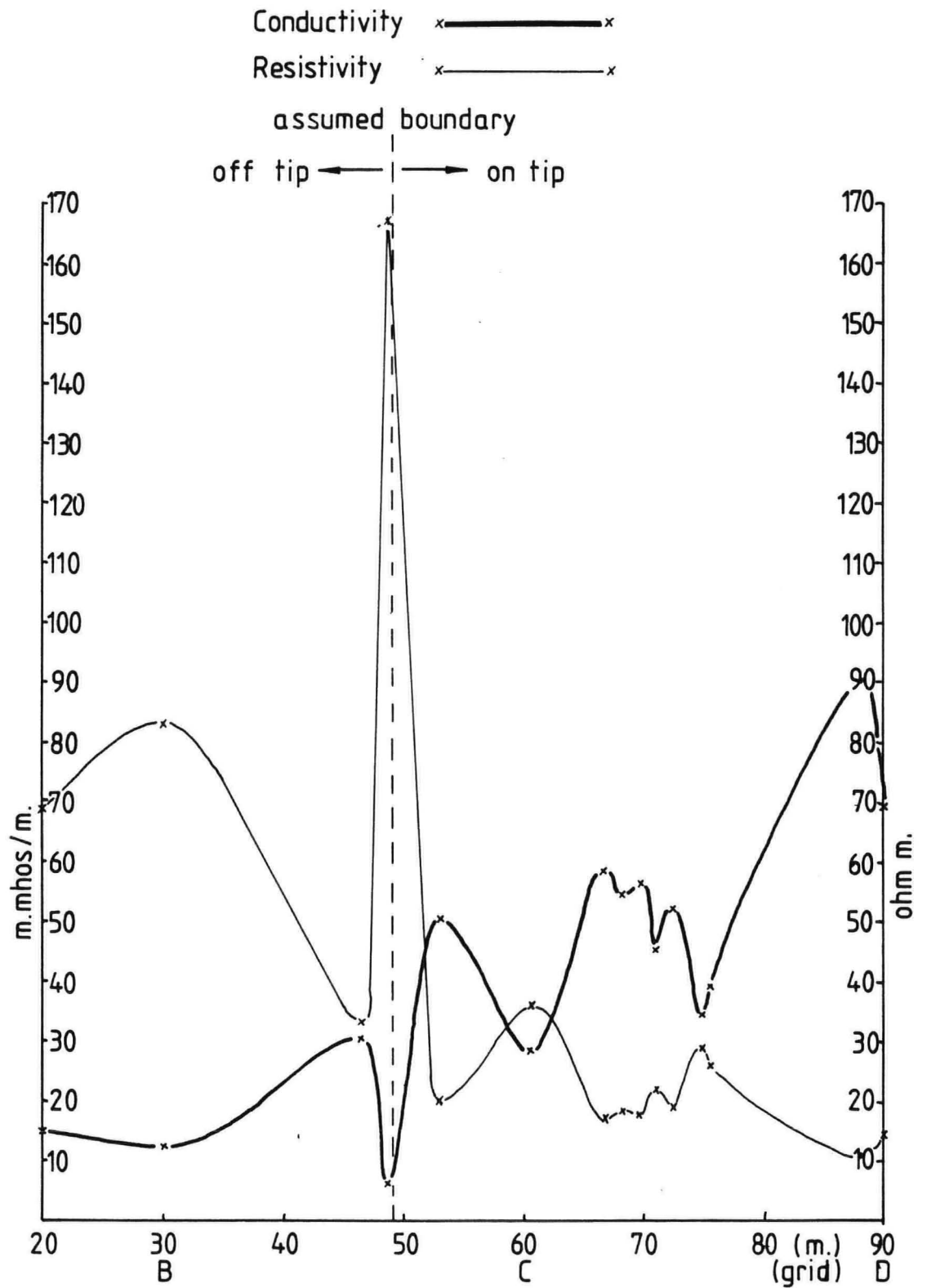


Fig. 5.10

Contour plan of apparent resistivity from EM 31 survey  
(readings converted to resistivity, averaged from dipoles N-S and E-W.) 3 November 1984

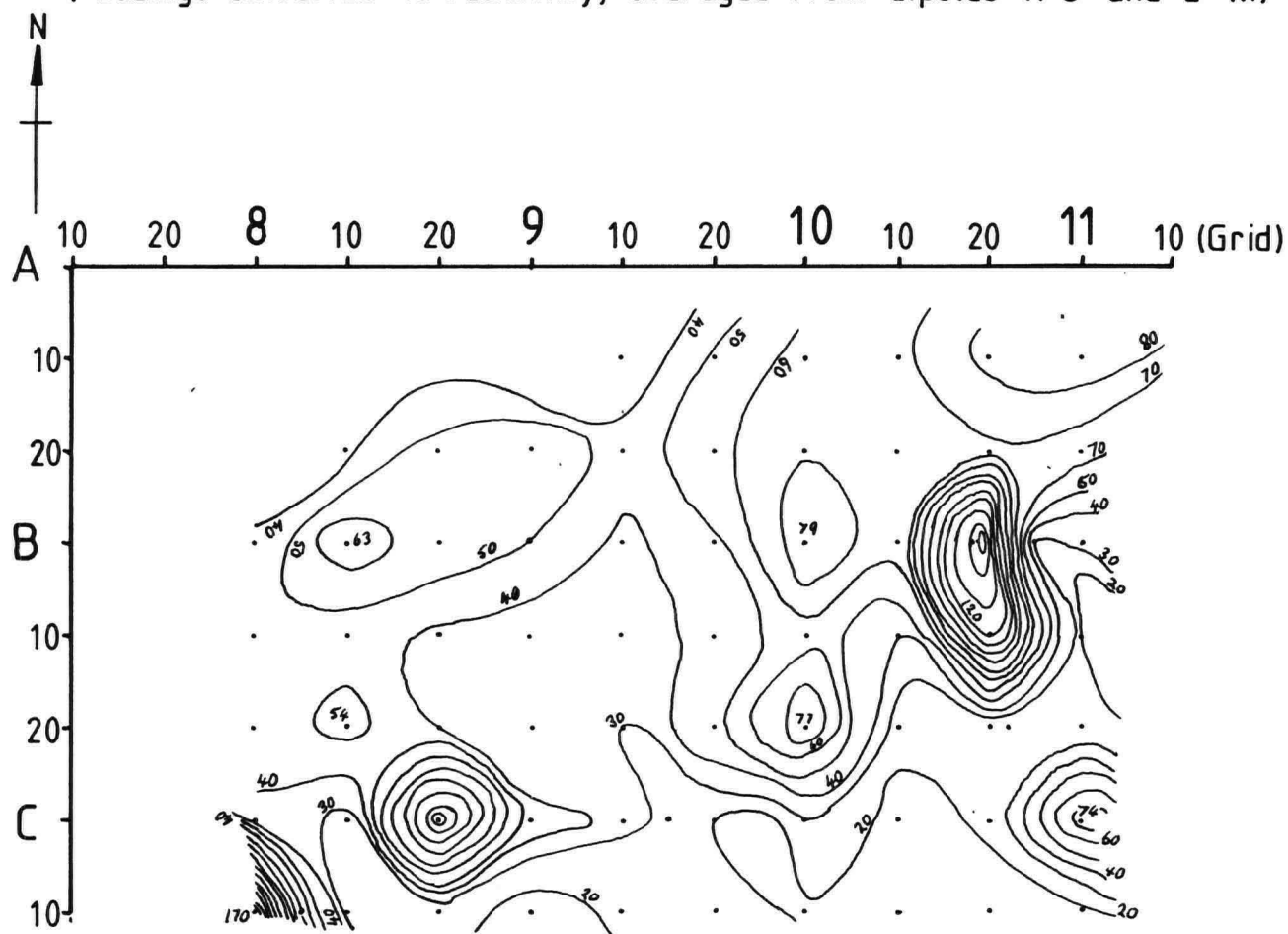


Fig. 5.11

other, and therefore, where the difference between the two values is large, a departure from the true ground resistivity is introduced. It is not evident that there is a linear high resistivity feature near to the boundary using this method of presentation. The similarities with the contoured plan of Wenner resistivity traverses will be discussed in Chapter 9.

As previously mentioned, the traverse on Line 4 does not show any abrupt changes in apparent resistivity at the boundaries. The gradient of resistivity is also small (0.8 ohmm/m). Two traverses were surveyed with closer station intervals than normal (i.e. 2m) across the southern boundary. This was to check that any small anomalies had not been missed as a result of the 10m station interval being too large. The traverses are reproduced on Fig. 5.12. It is apparent that no features were missed on this part of the line. The relatively smooth resistivity profile appears, therefore, to have been produced by a characteristic of the ground at this position. In addition to the possibilities mentioned above (variations in the dip of host/fill interface, of leachate infiltration and of lithology), it is possible that the smooth gradient may be caused by the obliquity of the traverse to the boundary (see Fig. 1.2).

North      LINE 4      EM 31 Traverse, 4 November 1984      South

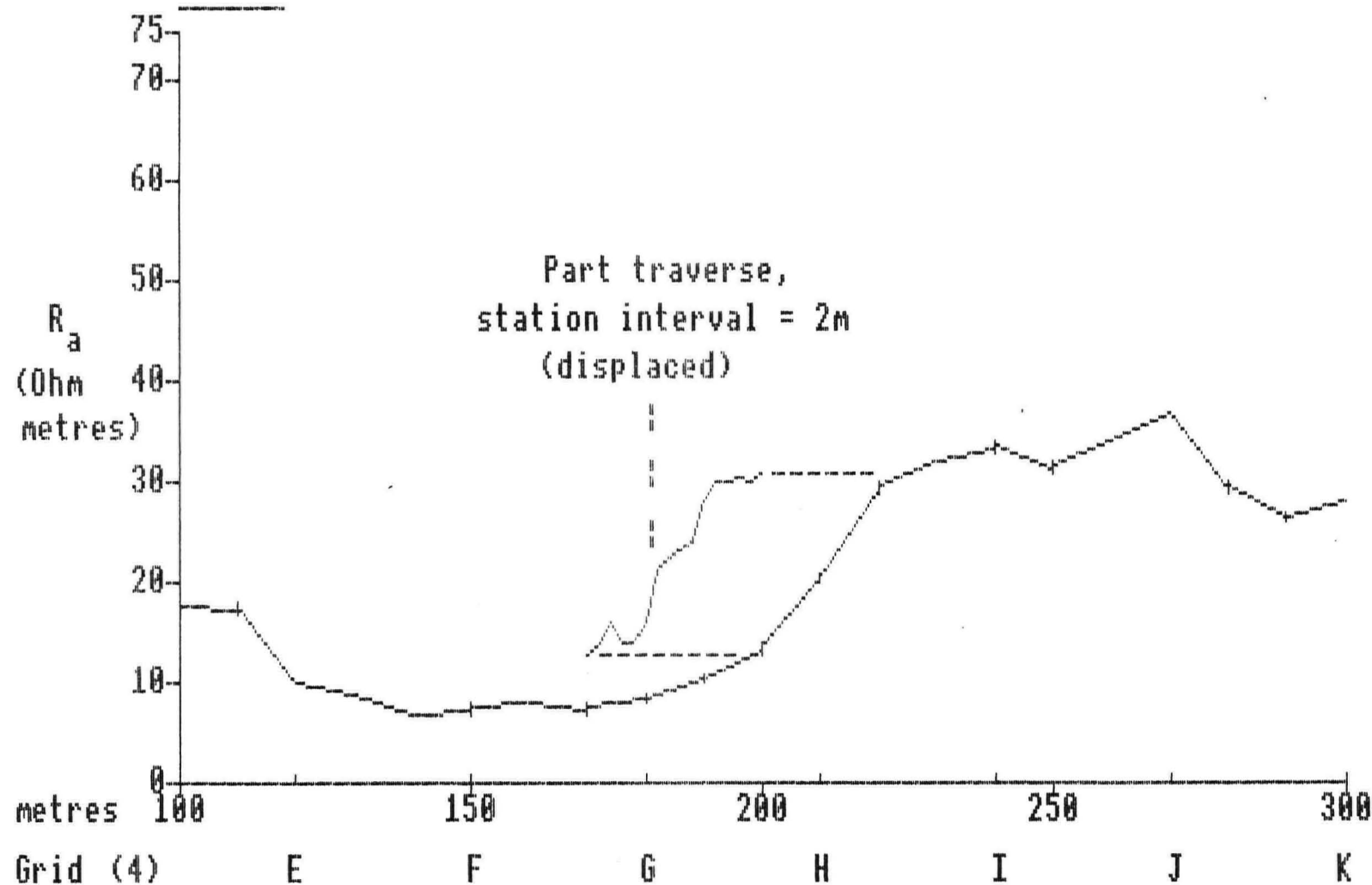


Fig. 5.12

### Repeatability

It was noted that where repeat readings were obtained the results were consistent. This was particularly noted on Lines 6 and 10 (Figs. 5.9 and 5.10) where the station interval was altered. When the position of the station coincided between the two surveys, so did the result.

A check was made specifically on the repeatability of the EM31 results on Line 4. The short 2m interval traverse discussed above was surveyed twice, once southward and once northward. There is no visible difference between the two sets of results when plotted to the scale of Fig. 5.12. The maximum difference was actually about 5% between the two traverses, which is in some cases less than the difference in readings obtained when the instrument is rotated about the vertical axis. The difference was greatest when the resistivity gradient was greatest. This implies that the cause was a positioning error. Similar results were found by Frohlich and Lancaster (1986). They found repeatability errors of 3.0 to 4.6%.

### Rotational Readings

The operating manual suggests that the presence and orientation of linear conductors can be detected by rotating the instrument in the horizontal plane about the operator and noticing the magnetic bearing of the maximum and minimum readings. This procedure was carried out on Line 8 and is reproduced on Fig. 5.13. The results are plotted as

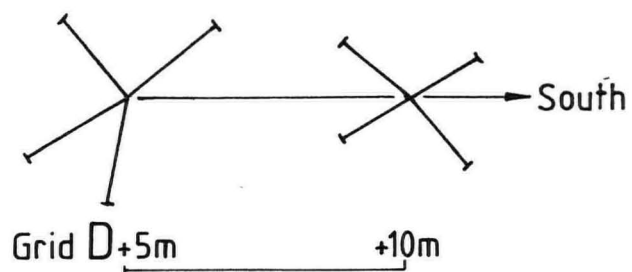
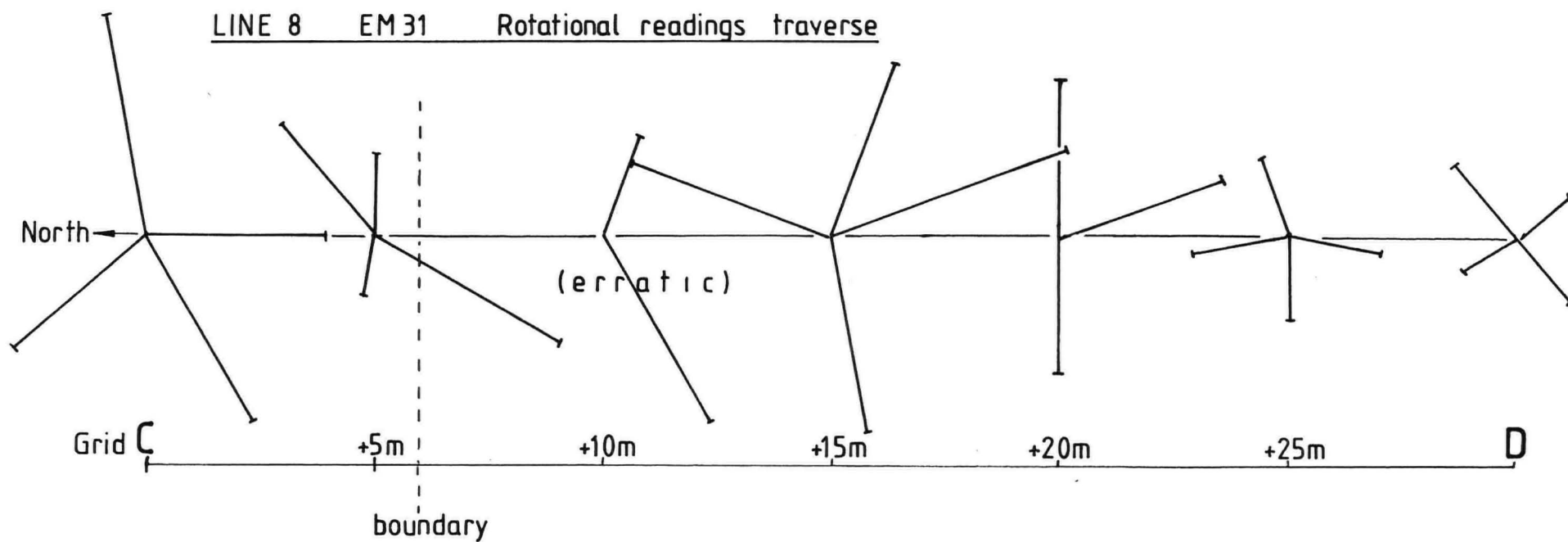


Fig. 5.13

vectors; the direction of the line shows the bearing and its length is proportional to the resistivity. Fig. 5.6 shows an anomaly between C and C+20m on the conventional traverse, Line 8. It is not apparent from the rotational readings that this anomaly exists, with the possible exception of one reading at C+10m, which tends to show an orientation in the direction of the boundary, but the readings were erratic.



### 5.3.3 Discussion

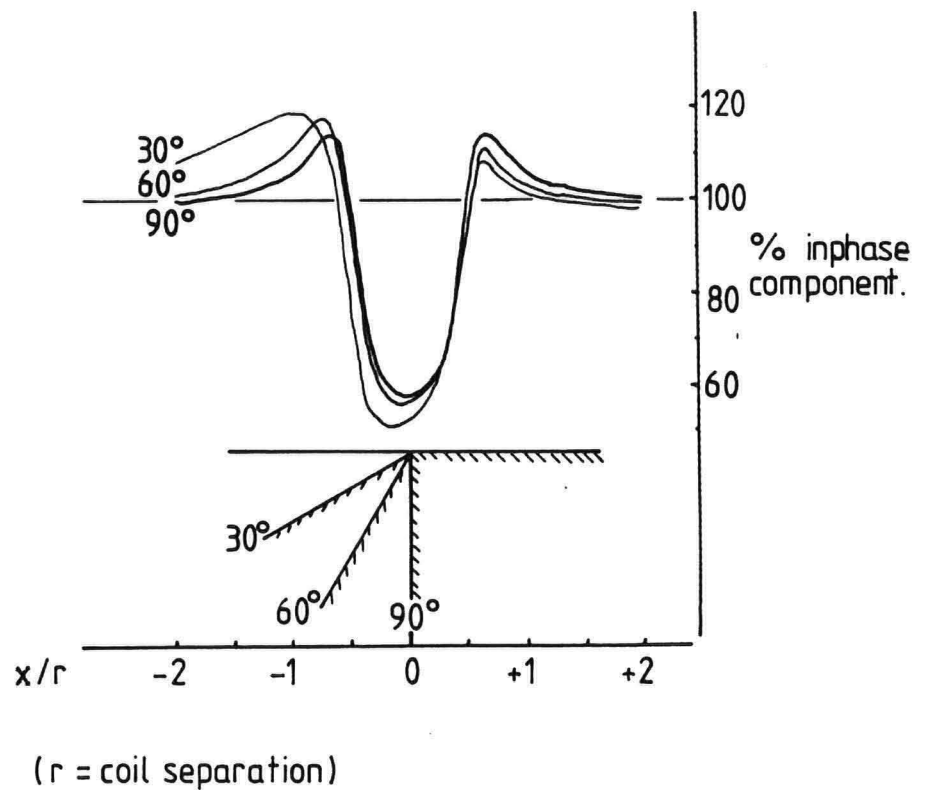
The predicted response of the instrument on either side of the boundary configurations shown in geoelectric models 2 and 3 (Figs. 4.13 and 4.14) have been calculated using the formula provided in the Operating Manual. The calculated response is included on the Figs. It is clear that Model 2 produces a closer approximation to the field response than Model 3, although the latter is based more closely on the resistivities and thicknesses derived from the resistivity soundings and boreholes. Calculation of the response on the sloping part of the interface is not valid as the formula assumes horizontal layers.

The profiles produced across the boundaries are not a smooth transition between the two resistivities. The shape of the profiles, which have been revealed in detail on Figs. 5.9 and 5.10, indicate the presence of a conductive body at the boundary, typified by a trough with two flanking peaks on the conductivity profile (see Fig. 5.14). Interpretation of the profile produced by fixed coil instruments in general is usually by reference to model curves. However, published curves are confined to the simple shapes; spheres, cylinders and conductive sheets (Keller and Frischknecht, 1966, Ogilvy 1986).

It is possible to exclude the cylinder from the possibilities by use of a rule-of-thumb procedure detailed in the EM31 Handbook. This states that the depth to a buried pipe is of the same order as the distance between the

E.M. Anomaly over a dipping conductive sheet

(Slingram response for depth of burial,  $d/r = 0.15$ )



from Keller & Frischknecht 1966

Fig. 5.14

two peaks on the profile. This is 6.5m on Line 10 and 5.4m on Line 6, both of which are too great to be realistic.

Of the model curves available for comparison with the field curves, those produced from dipping sheets are most likely to approximate to the expected ground configuration at the boundary. For example, it is possible that the clay lining, described in Chapter 1, could respond as a conductive sheet of limited depth.

Keller and Frischknecht (op. cit.) have listed the following characteristics, resulting from a dipping sheet, which alter the typical anomaly of a trough with two flanking peaks and which is centred over a vertical sheet conductor:

1. The anomaly becomes asymmetric with the peak on the down-dip side being greater than that on the up-dip side, and the trough being displaced down-dip.
2. The effect of a finite depth is to reduce the amplitude of the anomalies; for shallow dips, a second "trough" is introduced on the down-dip edge of the sheet.

The field curves do not fit the above characteristics very closely. The material either side of the proposed dipping conductor is of differing conductivity, which introduces an element of anisotropy into the profile and so is not necessarily indicative of the dipping sheet model. If this difference in conductivity is removed from the profile on Line 10 (Fig. 5.10), the peak and trough feature tends to

become more symmetric.

The profile on Line 6 shows that the assumed boundary is 6m to the south of the conductivity trough. The profile on Line 10 shows the trough to be coincident with the assumed boundary. It is possible therefore, that the boundary at the southern end of Line 6 has been positioned incorrectly in the site survey.

It appears that the anomalies at the boundary could also be the "edge effects" which are mentioned in the Operating Manual without further explanation or description. They occur at the junction of a good and poor conductor. The existence of metal in the waste material would provide this contrast. If metal collected at the base of the fill whilst it was being tipped and moved about, it is possible that a concentration of metal on the sloping sides could simulate a dipping sheet conductor.

#### 5.3.4 Conclusions

E.M. traversing produces a well defined anomaly at the host/fill boundary. In many locations on the landfill site studied, this feature could be more closely defined as a trough and two flanking peaks on the conductivity profile, typical of a conductor. The anomaly conforms most closely to the form of the profiles produced by a dipping sheet conductor. It is most likely to be caused by metal, and could represent a concentration in the clay lining.

There is reasonably close agreement between the derived response from geoelectric model 2 and the field profiles for the material either side of the fill/host boundary.

The method is quick. The continuous read-out facility enables rapid interpolation between fixed stations, thus enabling a more accurate definition of the shape of anomalous profiles. Alternatively, a variable station interval, dependant on the resistivity gradient, could be adopted. In areas of high apparent resistivity gradients it was found that the instrument responded to movement of 0.1m. However, the significance of this ability is dependent on the accuracy of the original survey; it may not be possible to locate the position of the instrument to this degree of accuracy. The method could be adopted to automatic data logging which would further speed up the data acquisition.

The variation in readings produced by changing the orientation of the instrument about the vertical axis is a

diagnostic feature which can be used to identify regions of large apparent resistivity gradients. The traverse using rotational readings show that this feature is not so useful when used on its own to determine the position of the large gradient. They do not provide any more information than the normal traverse, and on this site, do not convincingly indicate the existence and direction of a linear conductor.

A check on the repeatability of the readings showed that successive readings were within 5% of each other. The error was probably due to positioning errors in the regions of high conductivity gradient.

The traverses do not clearly suggest the existence of a steeply dipping fill boundary on the northern side and a more gently dipping boundary on the other side. This may be partly a consequence of the masking effect of the trough and peak features produced at most of these boundaries.

The width of the transitional part of the profiles is large (up to 80m), but this mis-represents the usefulness of the method. Inspection of the profiles shows that in many cases the boundary is centred on one of the resistivity peaks (or conductivity trough).

It is suggested from the results that the assumed position of the boundary at the southern end of Line 6 is 6m south of the actual boundary.

The success of the method on other sites would be dependant on the contrast provided by the host material, which depends on its lithology and on the ground water conditions, as was the case for resistivity traversing.

#### 5.4 E.M. Depth Soundings (Probes)

##### 5.4.1 Method

The Operating Manual for the EM31 describes how depth probes can be performed using the instrument. Curves are included in the Appendix of the Operating Manual which are said to enable the interpretation of two layer cases. As the fill was originally thought to be 3 metres thick, covered by a 0.9 metre thick clay cap, there was a possibility that it would have presented a two layer ground profile within the range of penetration of the instrument. A series of soundings was therefore attempted, based on the procedure laid out in the instruction manual.

Readings were taken at three stations on the fill and two stations on the host material. Conductivity readings were taken at each station at nine different heights, starting at ground level and increasing by 0.25m intervals to 2.0m above ground level. At each height, readings were obtained with the dipoles vertical and horizontal. At stations 6F and 10B two sets of readings were obtained at each height and dipole orientation by orientating the dipole in a N-S and E-W direction about the vertical axis. Both sets of readings are plotted. A non-conducting (wooden) step ladder was used to gain height.



#### 5.4.2 Presentation and Discussion of Results

The results of the EM31 soundings are plotted on Fig. 5.15. The soundings at grid references 6F and 2F coincide with the positions of boreholes, which enables a check to be made on the accuracy of the sounding interpretations.

The soundings have been interpreted using the curves for two layered ground published in the EM31 Operating Manual. In the case of borehole 6F, the top layer would be the 0.9m thick clay cap and the lower layer would be the fill. In the case of borehole 2F, the top layer would be the 1.5m thick predominantly sand and gravel and the lower layer would be the clay.

The procedure is illustrated below for the sounding at grid reference 6F (on the fill).

The first stage of the process required that the field curve is matched to one of the model curves. If no match is possible, the ground cannot be interpreted as two layers. The best fit curve for the sounding at 6F gives a value of top layer thickness (t) of 0.5m and a conductivity contrast

$$\frac{\sigma_2}{\sigma_1}(k) = 0.015, \text{ by interpolation.}$$

The two layer case is then resolved as follows:

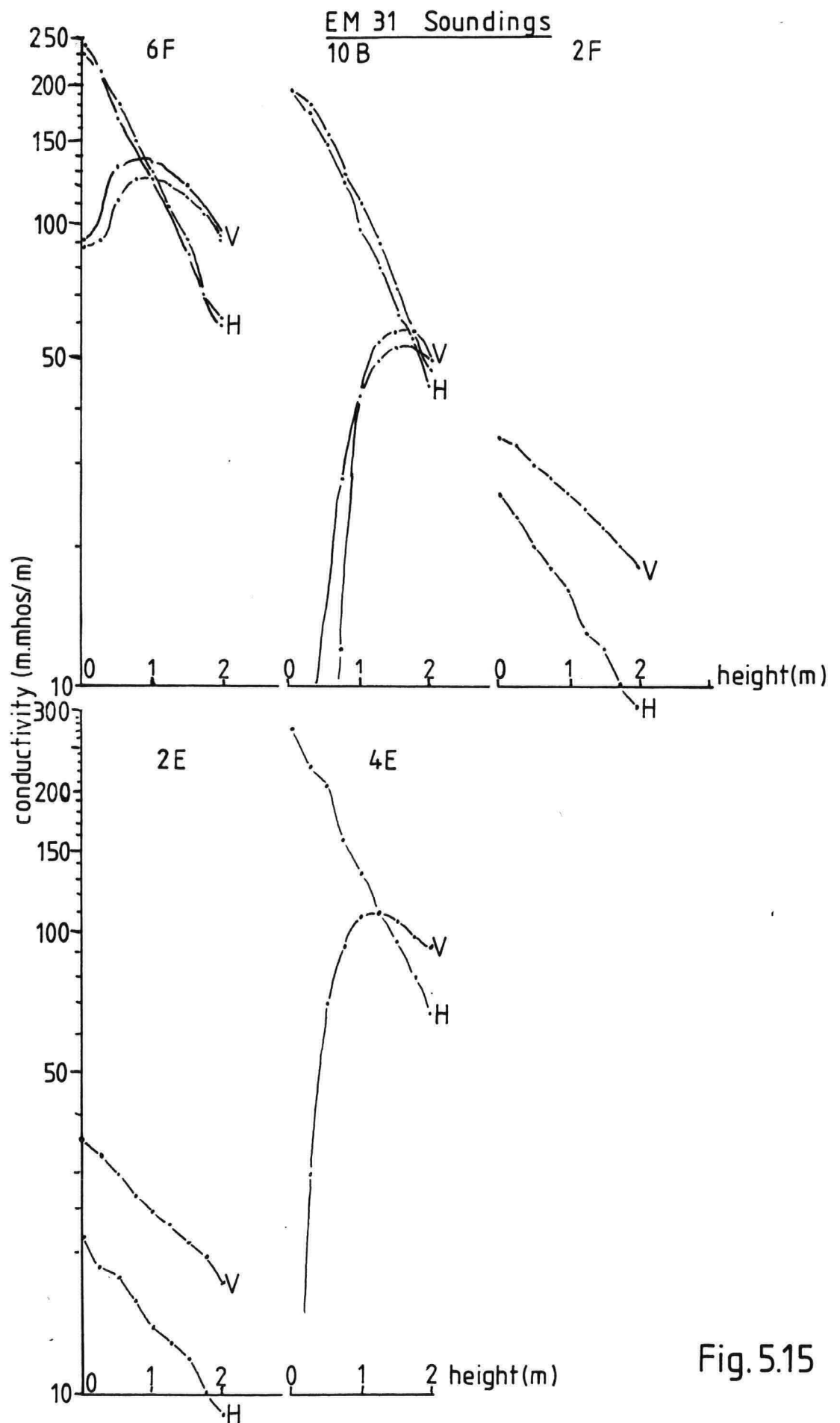


Fig. 5.15

By inspection, when the instrument reading (  $\mu v$  ) in the normal operating position (dipoles vertical) is 126 to 132 mmhos/m:

$$\frac{\sigma_m}{\sigma_1} = 0.115 \text{ from the graph.}$$

$$\sigma_1$$

$$\text{Therefore, } \sigma_1 = \frac{\sigma_m}{0.115} = \frac{0.5(126+132)}{0.115} = 1122 \text{ mmhos/m}$$

$$\text{From the curves } k = 0.015 = \frac{\sigma_2}{\sigma_1} = \frac{\sigma_2}{1122}$$

$$\text{and so, } \sigma_2 = 0.015 \times 1122 = 17 \text{ mmhos/m}$$

The interpretation for the sounding at 6F is therefore;

$$\text{Upper layer thickness} = 0.5m$$

$$\text{Upper layer conductivity} = 1122 \text{ mmhos/m}$$

$$(\text{Upper layer resistivity} = 0.9 \text{ ohmm})$$

$$\text{Lower layer conductivity} = 17 \text{ mmhos/m}$$

$$(\text{Lower layer resistivity} = 58.8 \text{ ohmm})$$

Comparison with the log for borehole 6F (see Appendix 2) shows a very approximate agreement between the predicted upper layer thickness (0.5m) and the known thickness of the clay cap (0.5 - 0.9m).

Comparison with the resistivity sounding interpretations (Fig. 4.18) shows no agreement at all. The E.M. interpretation shows an increase in resistivity from upper to lower layer, but the conventional resistivity sounding interpretation shows a decrease. The resistivity predicted by the E.M. instrument is suspiciously low (0.9 ohmm) (indicating a material which is unusually highly conductive) and is below the range of resistivity found in naturally occurring soils.

The interpretation of the soundings on the fill using the curves published in the Operating Manual is therefore suspect on this site.

The interpretation for the sounding at 2F (on the sand and gravel), using the previously illustrated method is:

Top layer thickness = 0.5m

Top layer conductivity = 0.68 mmhos/m

Top layer resistivity = 1470 ohmm

Lower layer conductivity = 34 mmhos/m

Lower layer resistivity = 29 ohmm

Comparison with the log for borehole 2F (see Appendix 2) shows no agreement with the known thickness of the sand and gravel layer (1.5m).

Comparison with the four layer conventional resistivity sounding interpretation (Fig. 4.21) shows little agreement in resistivity values, the top layer is 812 ohmm, but the resistivity does fall from the top to the lower layer in both the E.M. and the resistivity interpretations.

The seven layer resistivity interpretation, which produced the best fit curve, shows a similar top layer to the E.M. interpretation with a layer thickness of 0.5m and a resistivity of 1055 ohmm.

The results of the E.M. sounding interpretation suggest that the ground on and off the tip area cannot be interpreted in terms of a two layer model. Further quantitative interpretation was therefore not attempted.

The shape of the pairs of curves can be used to gain qualitative information about the variation in conductivity. The depth of penetration of the instrument with the dipoles vertical is about twice that with the dipoles horizontal. Therefore if the indicated conductivity from the two sets of readings is different, it shows that the ground conductivity varies with depth. The direction of the variation indicates whether the conductivity is increasing or decreasing with depth.

With reference to Fig. 5.15, it is clear that the three soundings obtained on the tip (6F, 10B and 4E) show a distinctly lower conductivity with the instrument at ground level and dipoles vertical than with the dipoles horizontal

at ground level. This therefore indicates a decreasing conductivity with depth (or increasing resistivity). As the instrument is raised the indicated conductivities for vertical and horizontal dipoles rise and fall respectively until an identical value is indicated for both dipole orientations at approximately 1 metre above ground level (the normal operating height). Thereafter both sets of readings fall.

The readings on the tip obtained at ground level with the dipoles vertical were often off-scale, i.e. negative. It is suggested that the instrument was giving negative readings in response to a highly conductive ground, as reported by Glaccum, et al (1983) and implied in the manual. It is another indication of the existence of metal in the tip.

The curves produced off the tip (2F and 2E on Fig. 5.15) show a higher conductivity with vertical dipoles than with horizontal dipoles. Therefore, resistivity decreases with depth. This fits the known geology which is sand and gravel over clay.

#### 5.4.3 Conclusions

EM31 soundings cannot be interpreted satisfactorily on the tip area. It is probable that the presence of metal has given anomalous readings resulting in the apparent increase in resistivity with depth, instead of the decrease noted from the conventional resistivity soundings.

The interpretation of the soundings off the tip are in agreement with the conventional resistivity sounding interpretation only in so far as they both show a decrease with depth. The values of resistivity derived from the EM31 interpretation do not agree very closely with the conventional resistivity interpretation but the top layer thicknesses are similar. The failure of the EM31 to produce sensible results in this case is probably because the ground cannot be simplified to a two-layer case (the best-fit resistivity interpretation required seven layers).

## 6.0 GROUND SELF POTENTIAL SURVEYING

### 6.1 Review of the Method and its Application to Landfill Sites

The self potential method utilises differences in voltage, produced by natural currents in the ground to indicate variations in ground composition. It is essentially a qualitative method. Various theories enabling interpretation of survey results have been published which rely on the correct assumption of the basic shape of the feature producing the anomaly prior to interpretation (De Witte, 1948, Yungal 1950, Meiser 1962, Paul 1965, Bhattacharya and Roy 1981). A complication arises from the number of mechanisms by which self potentials can be generated. An approximate rule of thumb interpretation, quoted by Telford et al (1976), states that the depth to the body producing an anomaly is equal to half the width of the S.P. profile measured at half the peak value.

The mechanisms of self potential generation are often divided into two types; mineralisation potentials and background potentials. The former tend to produce anomalies in excess of 100 mV, whilst the latter produce anomalies of a few tens of millivolts and hence have been regarded by mineral prospectors as a background "noise".

Mineralisation potentials are characteristically found over sulphide and graphite ore bodies. Sato and Mooney (1960)



suggested that the potential is generated by an oxidation and reduction cycle occurring above and below the water table respectively, with the ore body acting as the conductor of electrons from the reducing environment to the oxidising environment.

Of the background potentials, the most useful are "streaming potentials". The electron movement required for a potential to develop is produced by flow of the fluid containing the electrons. The voltage measured depends primarily on the pressure head causing the flow. Fluid flow may also be induced by thermal gradients. The mechanism has been shown to produce anomalies in excess of 100 mV, which in the absence of mineralisation potentials, makes streaming potentials easy to detect from other background potentials (Cooper and Koester 1984). Streaming potentials have been widely used in the USSR to detect seepage from reservoirs (Ogilvy and Ayed 1969; Bogoslovsky and Ogilvy 1970). The method has also been used to detect seepage from earth dams (Butler 1984).

Thermoelectric potentials are generated by temperature gradients across a soil or rock (Thermoelectric coupling). The phenomenon may be caused by the differential diffusion of ions and electrons in the pore fluid and rock matrix (Corwin 1984).

Finally, electrochemical concentration gradients occur between two zones of ground water which contain different concentrations of dissolved ions, inducing an ionic flow

between them. The voltages thus generated are known as diffusion or electrochemical potentials. It has been suggested that this mechanism could provide the basis for mapping subsurface contaminant plumes (Corwin op. cit.). It has also been suggested that a survey of such potentials be used to monitor leakage from hazardous waste sites (Markiewicz 1984). A grid of electrodes would be installed beneath the tip prior to filling and extended around the site. Readings taken over a time period would provide information on the shape and progress of any leachate plume.

The electrochemical concentration gradients and corrosion potentials arising from metal would both be possible sources of electrical potentials in waste tips. It is reasonable to assume that there would be an electrochemical gradient between the water contained within the waste material and the pore water of the host material. It is also clear that metal comprises part of most domestic and industrial waste. The method is therefore, one which may reveal information on the extent and content of waste tips.

There are two field procedures commonly used in self potential surveys (Telford et al 1976). In the first, the two electrodes, between which the voltage is measured, are advanced at a constant spacing along the survey line. This method therefore measures the voltage gradient. In the second method, one electrode is kept at the base station, usually away from the area of interest, whilst the second electrode is advanced. This method measures the voltage relative to the base station, which enables the results to

be plotted directly to reveal anomalies relative to the background potential.

## 6.2 Method and Equipment

Two sets of equipment were employed. Initially, copper electrodes surrounded by copper sulphate solution contained in porous wood probes were connected to an ABEM SAS300 Terrameter set in voltage measurement mode. Running averages of four readings were displayed. The input impedance of this instrument is quoted as 10 meg-ohms, which satisfies the method's requirement of a high impedance voltmeter. The second set of equipment comprised copper electrodes surrounded by copper sulphate solution in pots with ceramic bases connected to a Fluke High Impedance Voltmeter, model 8062A. A continuous reading was displayed.

The fixed electrode method of traversing was used. This method requires long cable lengths. When it was necessary to move the base station electrode, because of limited cable length, an overlap of three readings was ensured. The new base reading was adjusted to the original by adding the appropriate difference observed on the overlap stations. Care was taken to ensure uniform polarity between traverses. The same electrode and terminal on the voltmeter were used as the base in all traverses.

The following routine procedures were also followed. Readings were taken when the electrodes were placed adjacent

to each other at the base station to check that the voltage registered was zero or near to it. A difference of  $\pm 2$  mV was considered tolerable (Telford et al, 1976). In the case of the ceramic pot electrodes, grass was cleared away to expose the topsoil to provide good ground contact. The wood probe electrodes were buried in pre-formed holes. The ground was moist during all surveys and so water was not added as a routine procedure. The surveys were carried out between September 1985 and May 1986.

### 6.3 Presentation of Results

The results obtained using the ABEM Terrameter are shown in Fig. 6.1. The polarity on Fig. 6.1 has been reversed to facilitate comparison with the results obtained using the Fluke voltmeter (Figs. 6.2 - 6.4).

Problems were encountered with the ABEM equipment and not all the results are reproduced here. It was found that the readings tended to vary with time and were affected by the amount of moisture around the electrodes. As a check on the equipment, the electrodes were placed in a copper sulphate bath and readings were taken. The variation continued in a random manner. It was therefore difficult to distinguish variations which were inherent in the system from those which may be a feature of the ground.

Some of the more stable results are shown in Fig. 6.1. They are suspect on their own. However, they show some similarity

West      LINE E      SP Traverse (ABEM terrameter)      1 December 1985      East

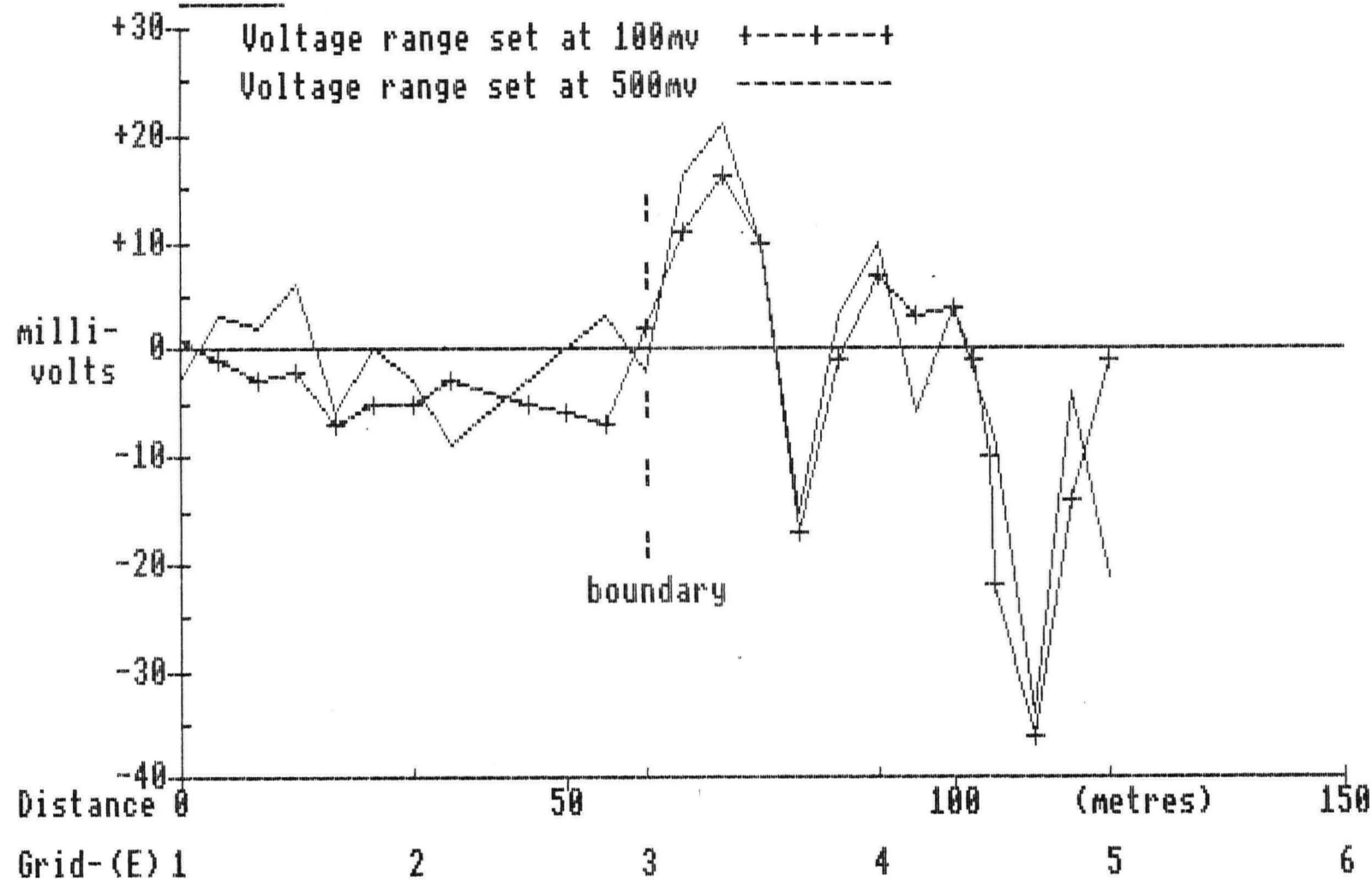


Fig. 6.1

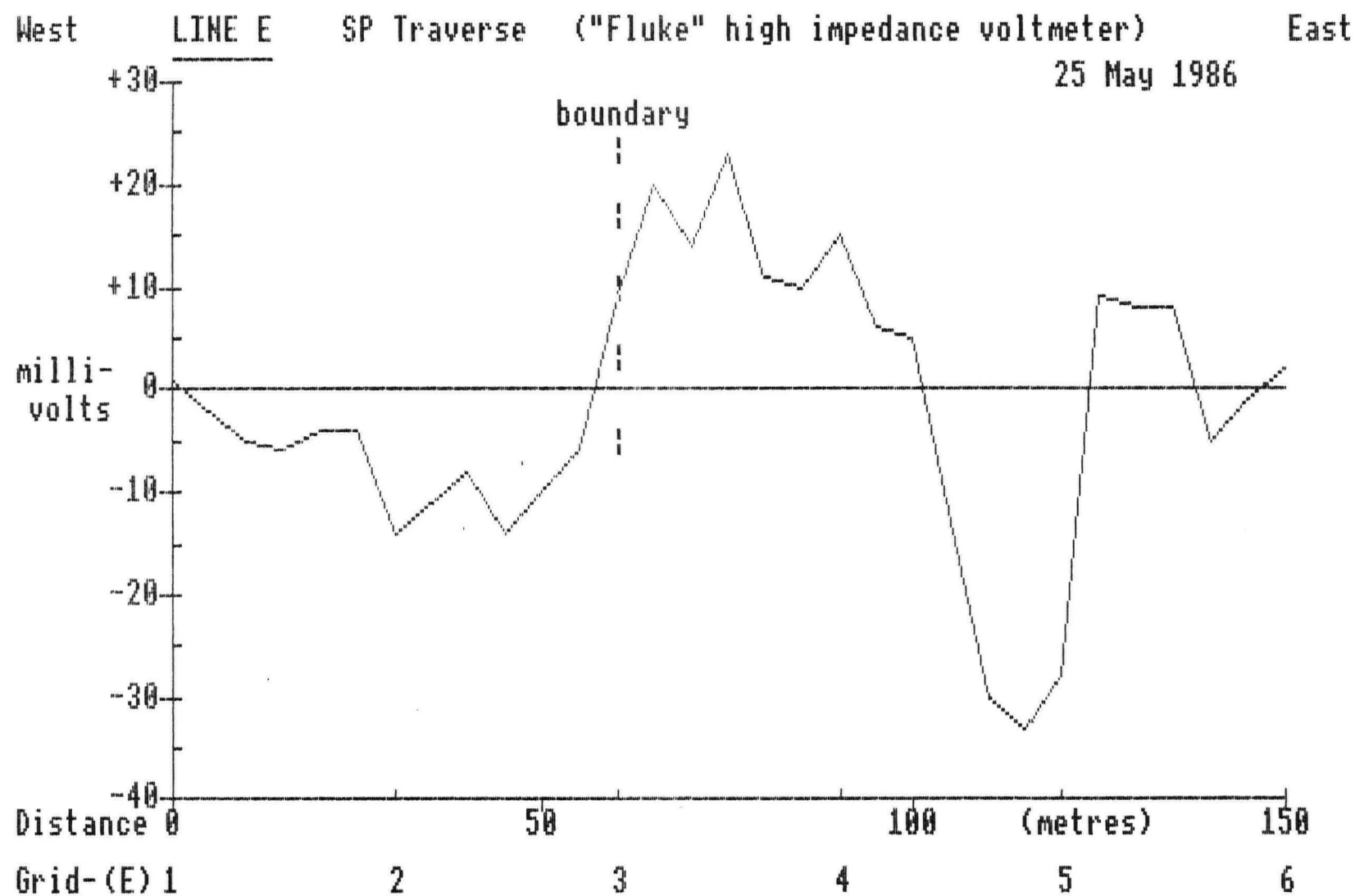


Fig.6.2

with the corresponding measurements taken with the Fluke voltmeter (Fig. 6.2).

The results obtained with the Fluke voltmeter and ceramic pot electrodes were generally more stable. The continuous reading display gave immediate notice of any instability. When this occurred, it was generally cured by improving the contact with the ground. In no case was it necessary to add water to the ground with this equipment. It was only necessary to clean off any accumulated mud from the base of the pots to maintain stable readings.

Fig.6.2 shows a traverse across the west boundary on Line E. The voltage variation off-tip is 15mV, and on-tip it is 56mV. The departure from zero off-tip reaches -14mV. There is a positive anomaly at the boundary of 20-23mV, extending over 35m. It is adjacent to a larger anomaly of opposite sign centred at grid number 4+25m.

Comparision with Fig.6.1 which shows two traverses on Line E obtained using the ABEM equipment, indicates some similarities. There is again a negative anomaly centred at 4+25m and a positive anomaly at the boundary, although the latter is less distinct than the peak in Fig. 6.1. These features were evident using both instruments where the electrodes were not wetted. These anomalies were not present when the ABEM instrument was used and the electrodes wetted (which otherwise gave more stable readings with that instrument). The width of the anomaly at half the peak value is approximately 8.75m. Using the "approximate rule" the depth

to the body producing the anomaly at 4+20/4+25m on Line E would be  $0.5 \times 8.75\text{m} = 4.4\text{m}$ , which is a plausible result.

Fig. 6.3 shows a full length traverse on Line F. It is immediately apparent that the readings off the tip show less variation than those on the tip. The readings off the tip are within 7mV of each other (and are close to zero), whereas on the tip they vary by 92mV. At the west of the traverse, where the base electrode was initially placed, the readings are within  $\pm 4\text{mV}$  of zero. At the east end of the traverse, they vary from  $+ 3\text{mV}$  to  $+ 7\text{mV}$ . The slight positive offset from zero may be a cumulative error resulting from the changes in base station necessary on this traverse.

There is a distinct positive anomaly of like-sign at both boundary positions. The anomaly is 39mV and is spread over five readings at the west boundary (25m) and is 70mV and spread over six readings at the east boundary (30m). In both cases on this traverse the width of the anomaly at half the peak value is approximately 13 metres. This rule of thumb interpretation places the depth to the body responsible at 6.5m, which is deeper than is realistically possible.

Fig. 6.4 shows the Fluke voltmeter traverse on the southern end of Line 6. This traverse is a continuation of that on Line E, taken at right angles to it, starting at grid number 6E. Thus the base electrode is the same as for that traverse. Generally, the same features are reproduced on



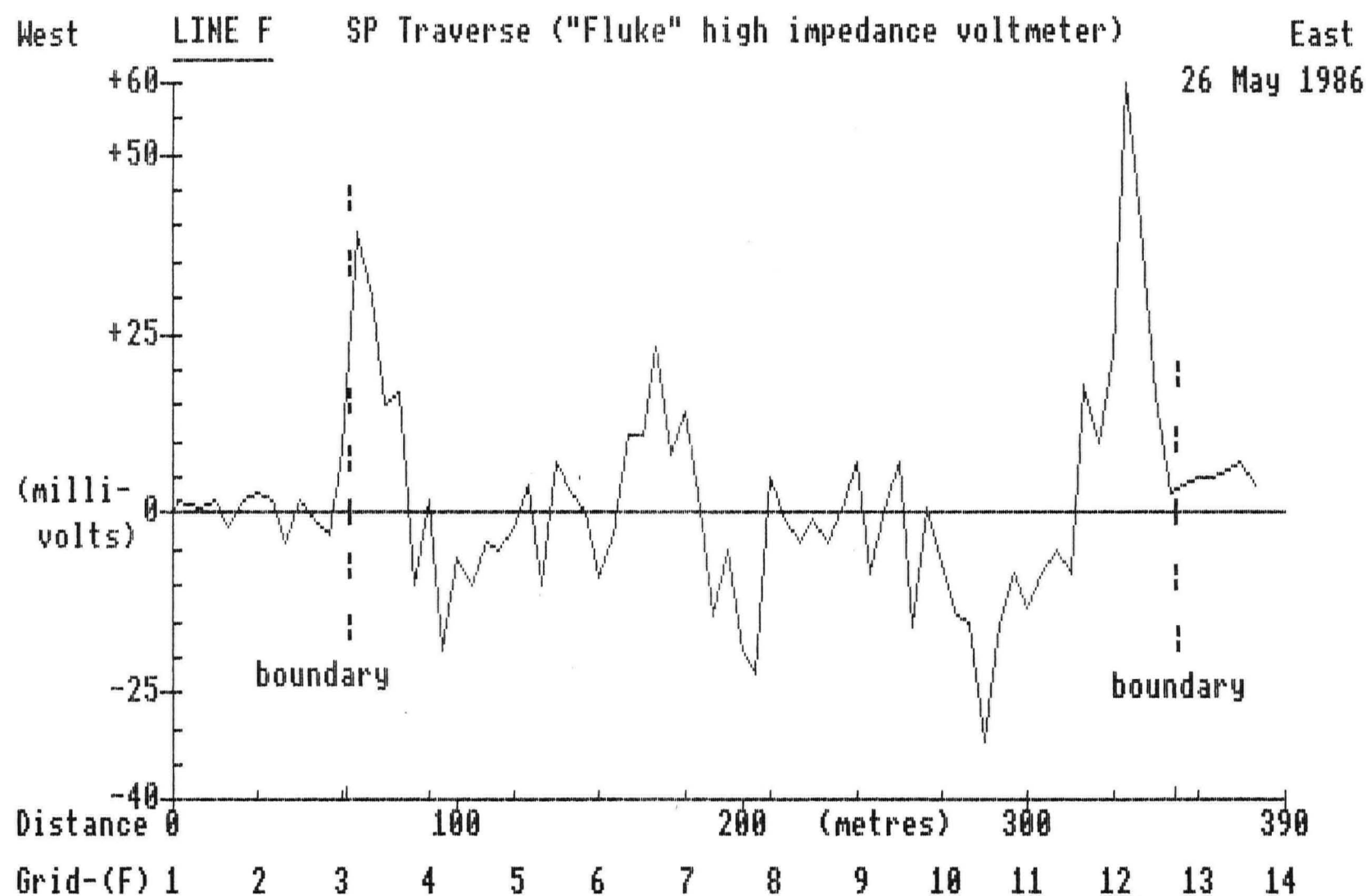


Fig. 6.3

North LINE 6

SP Traverse across southern boundary  
("Fluke" high impedance voltmeter)

South  
25 May 1986

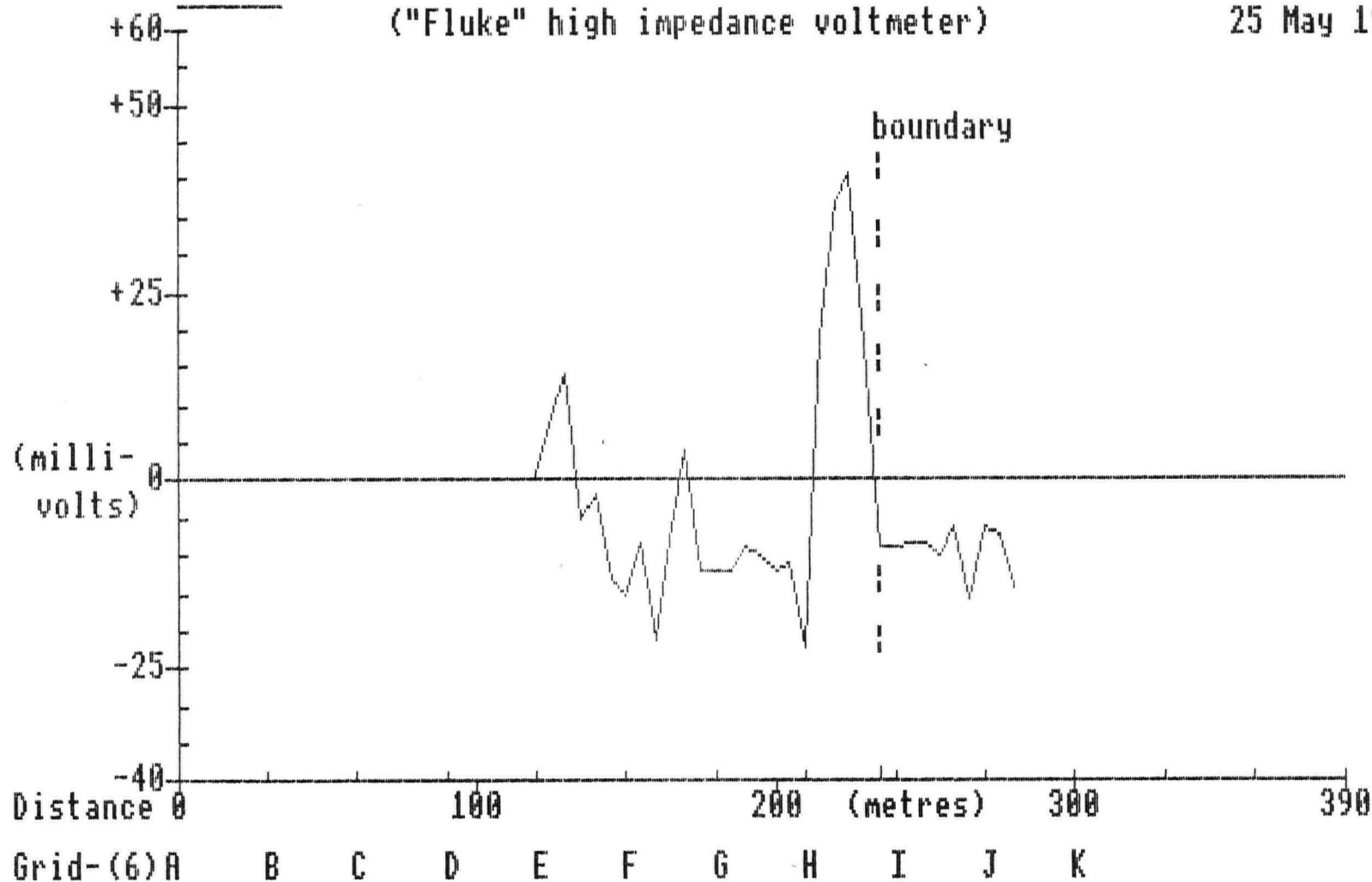


Fig. 6.4

this traverse as on the previous ones. The voltages are less variable off-tip than on-tip, being 10mV and 63mV, respectively. The departure from zero off the tip on this traverse is more marked (-10mV) compared with that on Fig. 6.3, but this may be a cumulative error associated with the change in base stations. There is a large positive peaked anomaly of +40mV across the boundary. The width at half the peak value is 17m, which using the approximate method of interpretation places the depth to the generating body at 8.5m, which again is deeper than is realistically possible.

#### 6.4 Discussion

Interpretation using the half width of the anomaly as an indication of the depth to the generating body clearly does not give realistic results at the boundary. This suggests that at this position the source is not a well defined body (such as a piece of metal) but is more diffuse. The negative peak at 4+20m on Line E could be a piece of metal as the apparent depth coincides with the assumed base of the fill.

The source of the potential at the boundary is probably an electrochemical concentration gradient. This would originate from the difference in ionic concentration in the pore waters of the host material and the waste. The shape of the anomaly is not affected by the topography. This is shown by the traverses on line F (Fig. 6.3) and on line 6 (Fig. 6.4). The former crosses the boundary where there is a distinct topographic feature. The latter crosses it where the topography is relatively flat, (where the alternative mechanism, streaming potentials, are unlikely to develop). It is possible that streaming potentials may be developed on the north boundary where the ground slopes away steeply beyond the tip boundary. In the circumstances the anomaly would not coincide with the tip boundary, although potentially useful information would be obtained.

The source of the potentials evident in within the filled area could be either local concentrations of leachate capable of producing electrochemical gradients, or possibly

corrosion potentials associated with metal. Metal is readily detected by other electrical methods and by the magnetic method. Therefore, comparison of self potential traverses with a method known to be capable of detecting metal would be of interest. This will be discussed further in the general conclusions.

Much of the variation in potential measured in the filled area also could be due to shallow effects originating from the clay cap. For example, they could be caused by local corrosion potentials and electrochemical potentials, both arising from the effects of the inclusion of artefacts or imported natural material in the clay cap.

#### 6.5 Conclusions

Self Potential traversing is capable of producing anomalies of like sign at the position of the tip boundaries. The anomaly is in the form of a well defined peak, although one traverse obtained with the Fluke voltmeter (Fig. 6.3) produced a less well defined feature. The form of the record produced on the fill material is erratic compared with the record produced over the host material.

The method is relatively quick. It was not necessary to wait for the electrodes to settle down before stable readings were obtained. As only one electrode is moved between stations, interpolation between stations is easy if necessary. The direct reading of voltage, continuously

displayed, assists the recognition of anomalous regions.

No information on the vertical extent of the features producing the anomalies is available from the surface Self Potential method. It is inferior to other electrical traversing methods in this respect because, for example, both resistivity and E.M. traversing afford the opportunity of adjusting the penetration depth of the traverse to some extent.

The method is probably most suitable for detecting "streaming potentials" rather than the smaller magnitude potentials measured in this study. The application to waste tips would be to the monitoring of leachate plumes in the host material. (Corwin 1984, Markiewicz 1984).

## 7.0 MAGNETOMETER TRAVERSING

### 7.1 A Review of Similar Applications

The Proton Precession magnetometer and the portable Flux-gate magnetometer are the two types of instrument most commonly used for engineering site investigations. The former was available for use in this survey.

The proton precession magnetometer measures the total field strength to the nearest gamma ( $1 \times 10^{-5}$  oersted). It responds to the ferrous content of materials which affects their magnetic susceptibility. Its sensitivity, portability and ease of use, have made it a suitable instrument for use in engineering site investigations. Raybould and Price (1966) and Hooper and McDowell (1977) have reported its successful application to the detection of buried mine-shafts. The anomalies produced by the mine-shafts in the latter report, were of the order of 100 gammas or less. Hooper and McDowell (op. cit.) state that these small anomalies are produced by differences in magnetic susceptibility of the shaft infill in comparison with the host material and not by metal. They also found that the small anomalies could be regarded as 'monopoles', whereas metal produced anomalies which were clearly dipoles, and of larger amplitude. Brick lined shafts were located successfully by Raybould and Price (op. cit.)

It would appear possible, therefore, to extend the use of

the proton precession magnetometer, to the detection of larger infilled areas, such as waste tips without the pre-condition that the waste should contain metal. Koerner et al (1982) and Benson and Glaccum (1980) have applied the method to the detection of buried metal drums containing hazardous waste, but there appears to have been no reported work on the application to landfill. It has the advantage that the contrast with respect to the host material is not dependant on anything else but the nature of the fill, unlike some of the previously described electrical methods.

## 7.2 Method and Equipment

The site at Panshanger was surveyed Lines C, E, G, 4, 6, 8, 9 and 11 (see Fig. 1.2) using a Geometrics Proton Precession Magnetometer. At least three readings were taken at each station. Station intervals varied from 1 metre to 10 metres, depending on the gradient. The instrument was held 2m off the ground and orientated approximately normal to the inclination of the earth's field. (This was the optimum orientation, but not mandatory). Readings were taken at hourly intervals at a base station to enable correction of the data for the variation in the earth's field. The usual precautions were taken to remove all ferrous objects from the operator during the survey.



### 7.3 Presentation and Discussion of Results

Eight magnetometer traverses are presented as Figs. 7.1 to 7.8. The first three traverses are orientated north-south, the rest are orientated east-west. The readings are presented as departures from the background field strength in gamma units. The background field strength at the time of the survey was approximately 48100 gammas.

All traverses show a very marked difference in the uniformity between the readings on the tip and those off the tip. The northern end of the north-south traverses and both ends of the east-west traverses show a smooth reduction in field strength as the boundary is approached. Further readings in the direction of the tip are erratic. The maximum reduction in field strength is in the order of 2000 gammas (see Fig. 7.1), although at the east end of line G it is only 100 gammas (see Fig. 7.3). Generally, there is a negative anomaly at the northern boundary of at least 1000 gammas, and a positive anomaly of 600 to 1500 gammas at the southern boundary (see Figs. 7.4 - 7.8).

The magnitude of the anomaly near the boundary and the erratic profile over the fill, show that there is metal present. The steep gradient of the profile, especially on the northern boundary, indicates that the source is shallow.

Interpretation of total field profiles is based on simplified models which comprise single or multiple dipoles or monopoles (the latter applies where one pole is

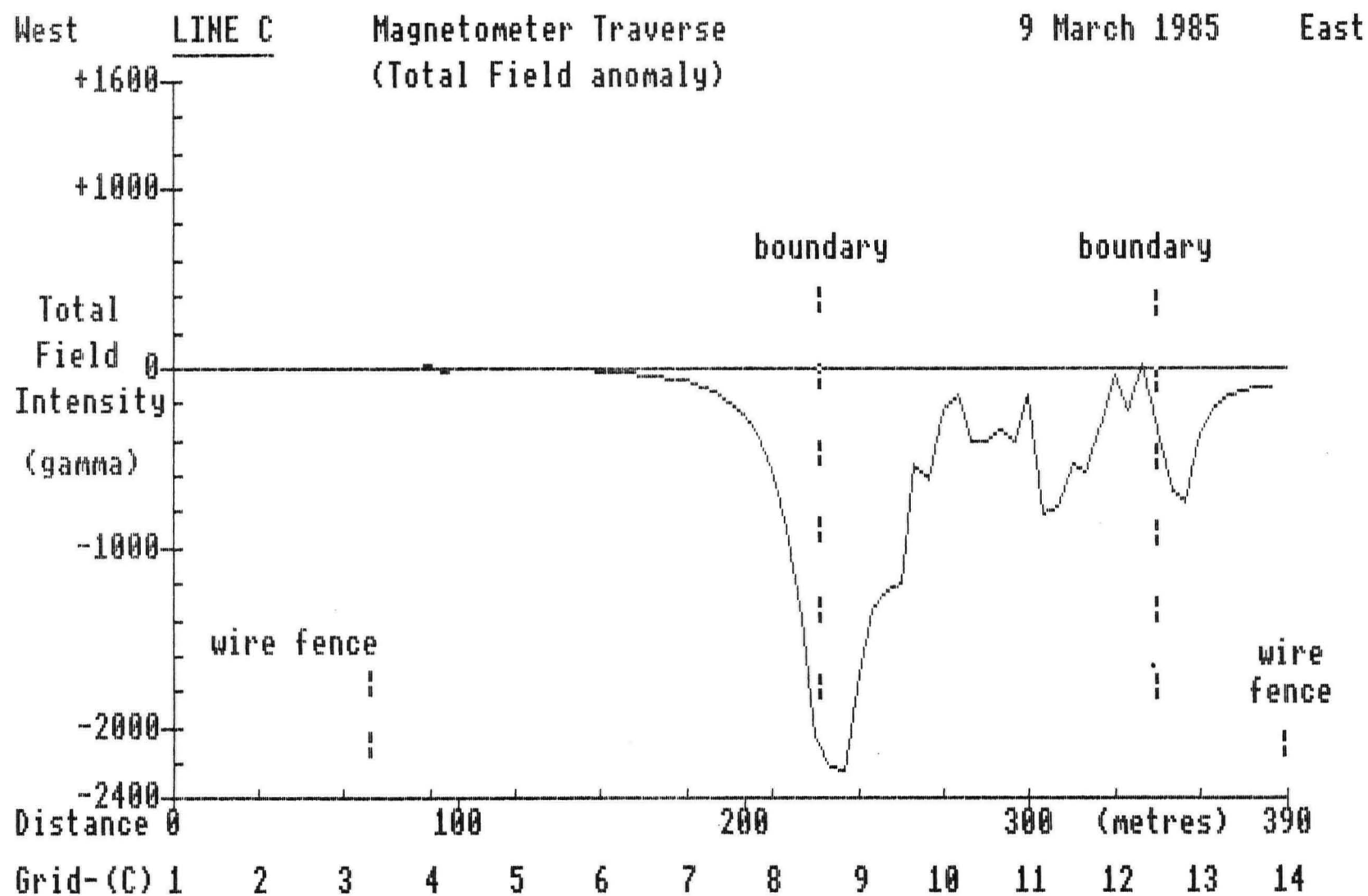


Fig.7.1

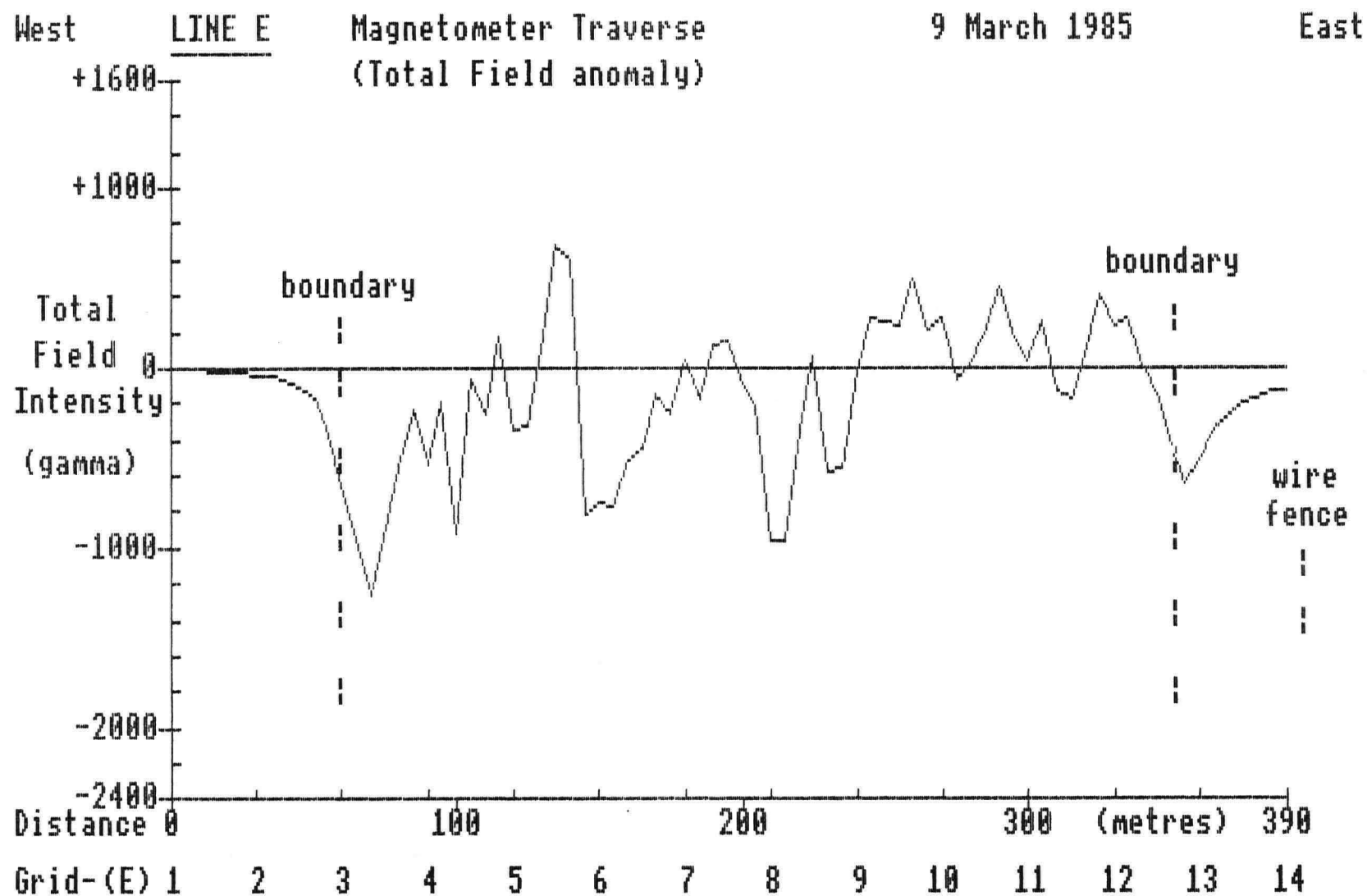


Fig.7.2

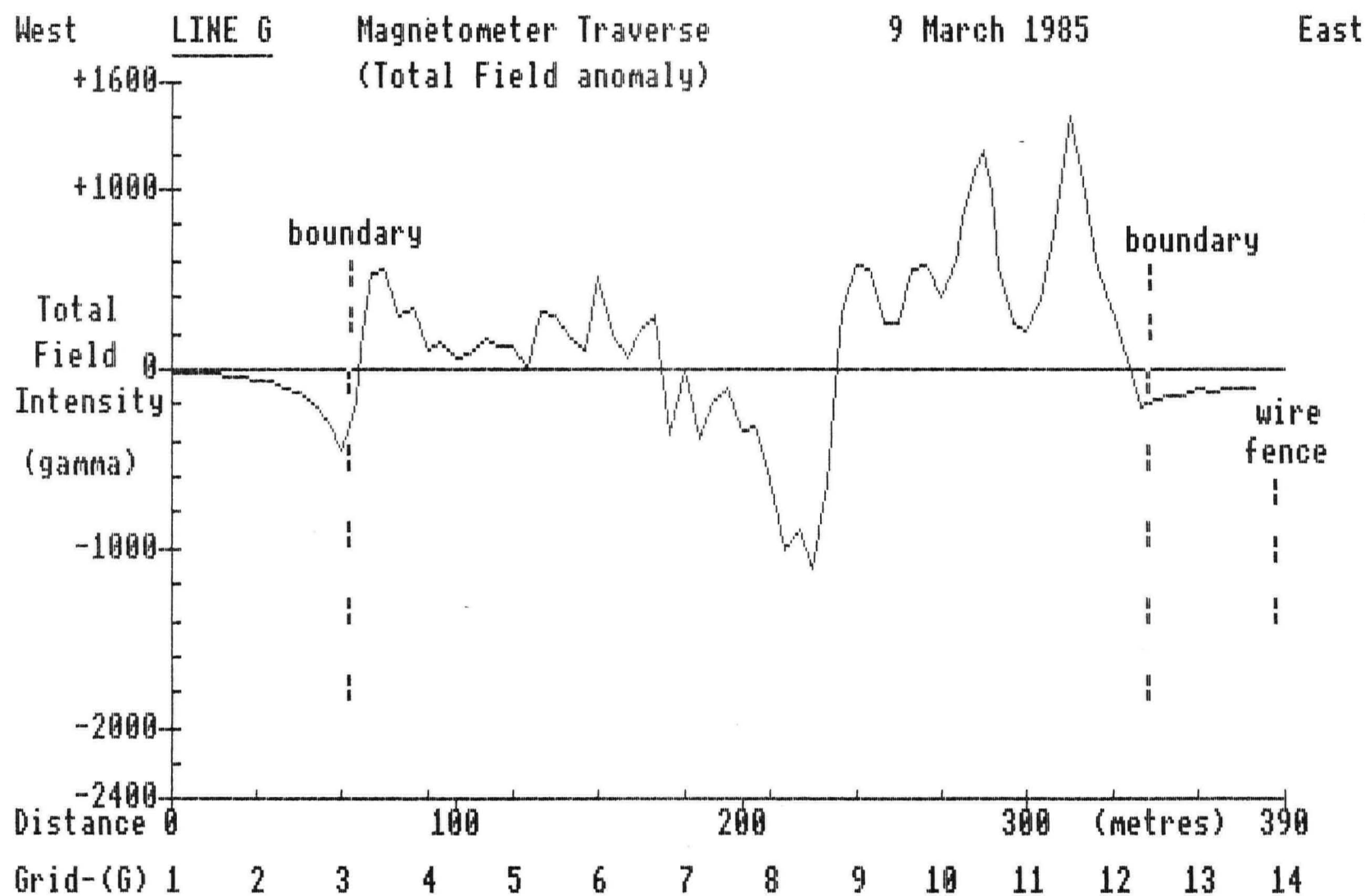


Fig.7.3

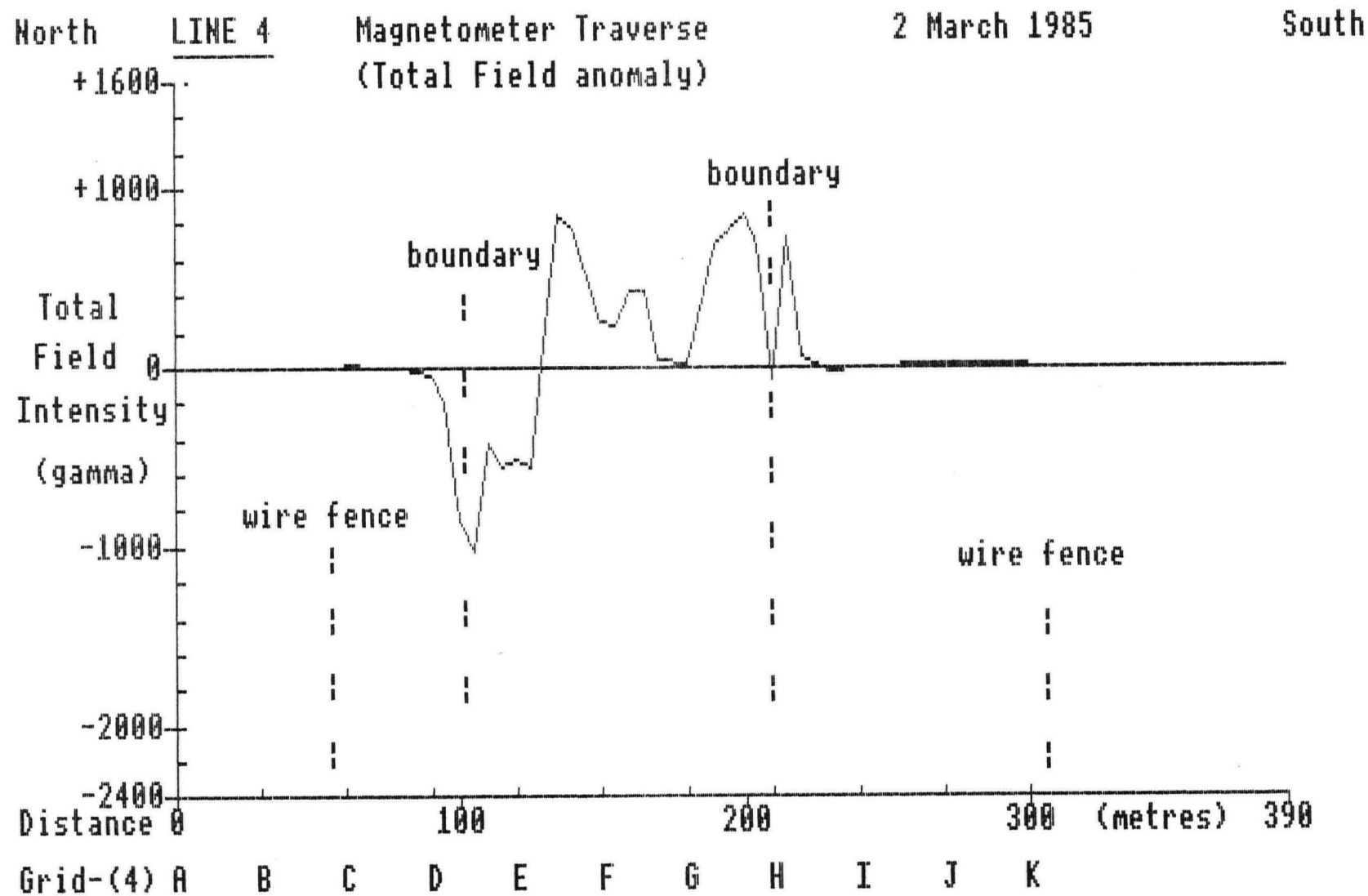


Fig. 7.4

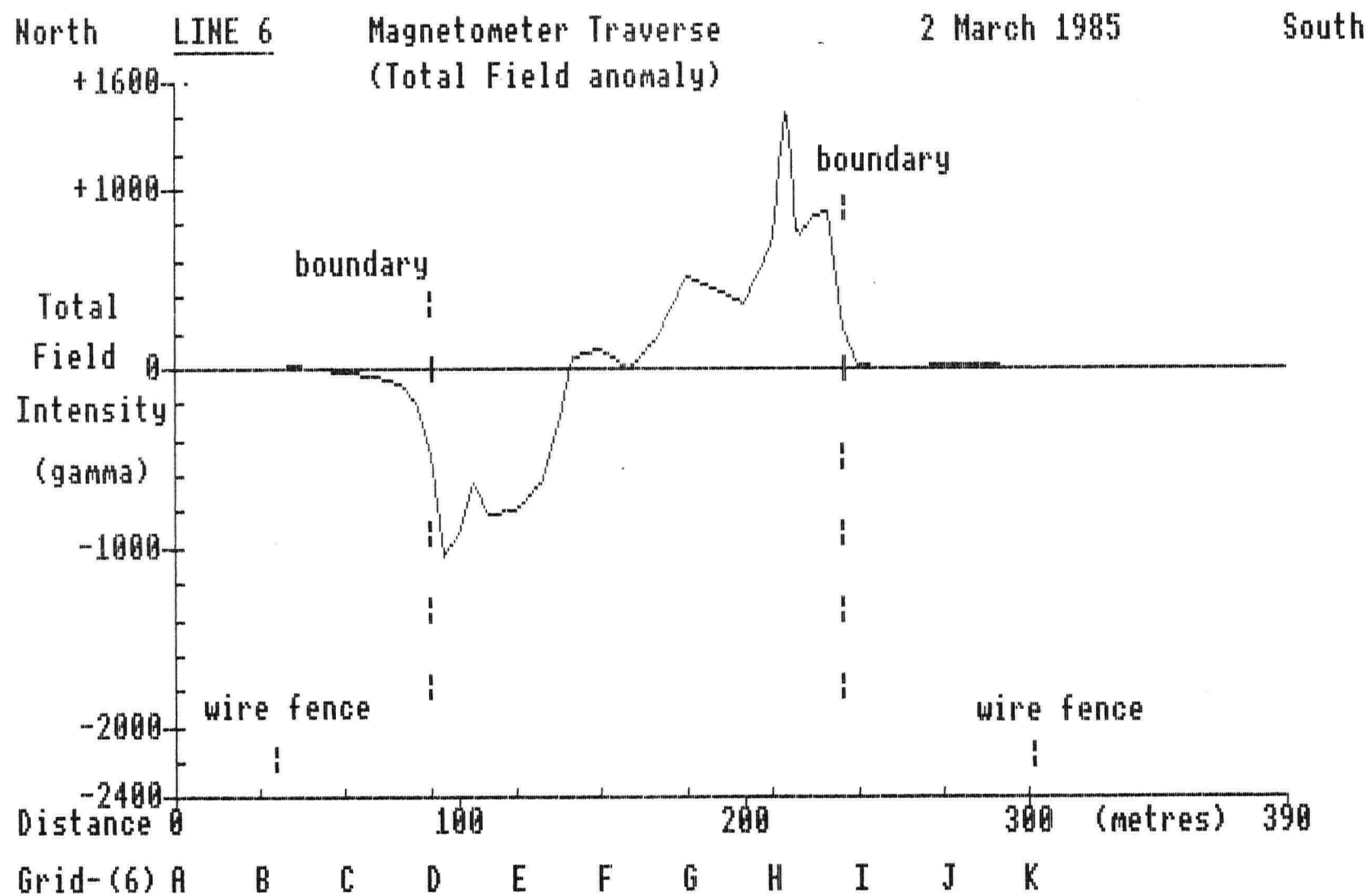


Fig.7.5



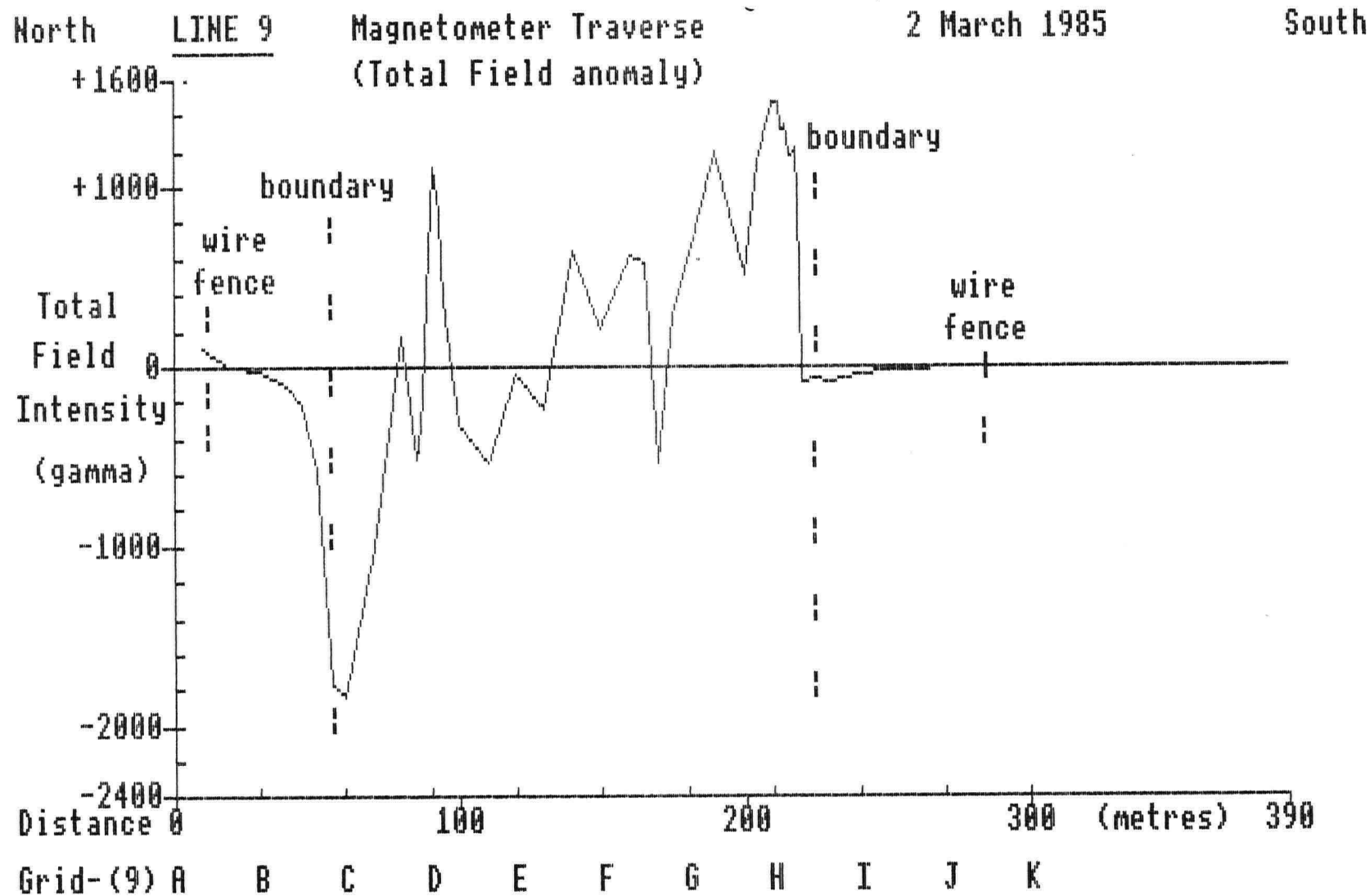


Fig.7.7



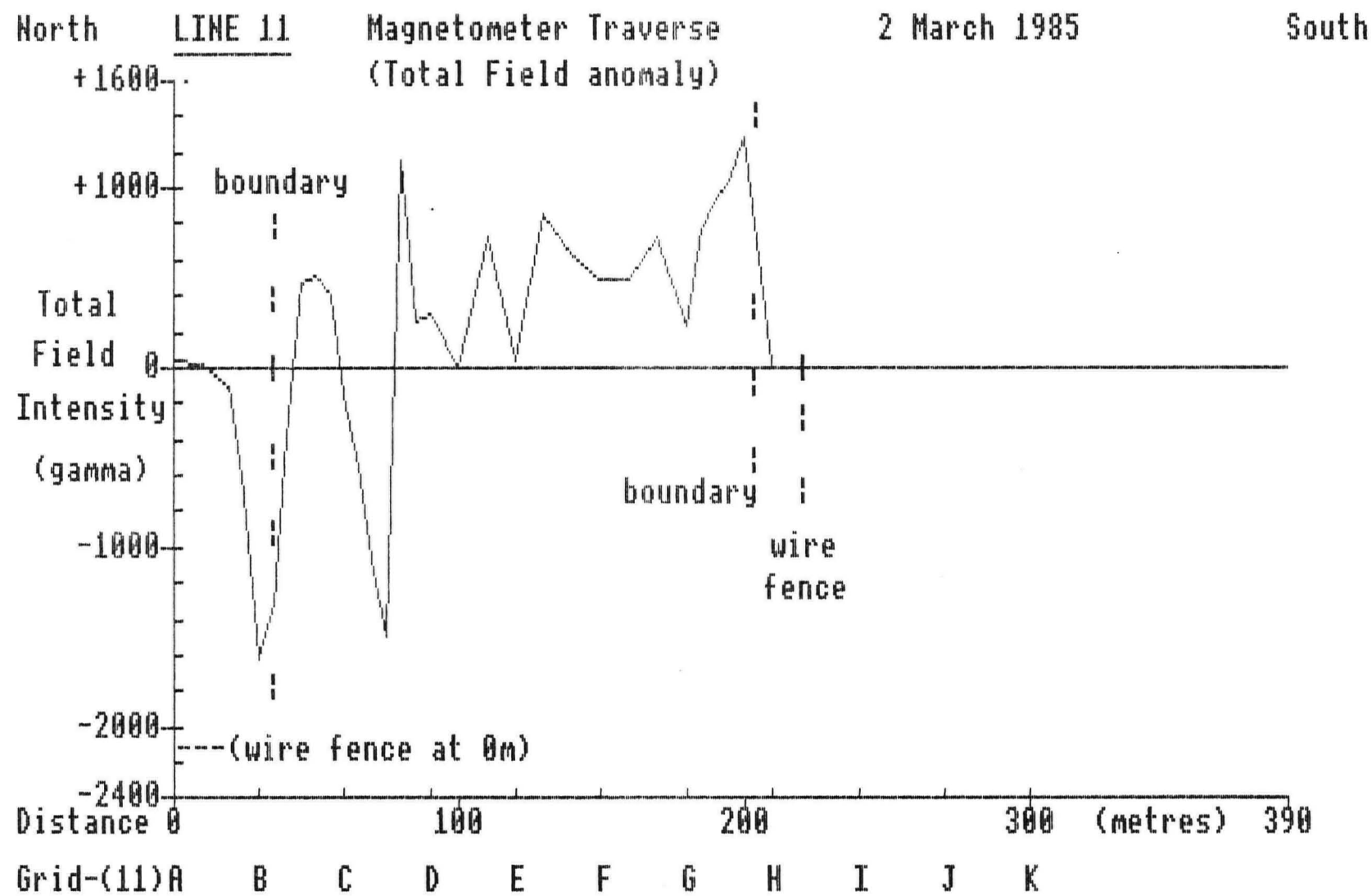


Fig. 7.8

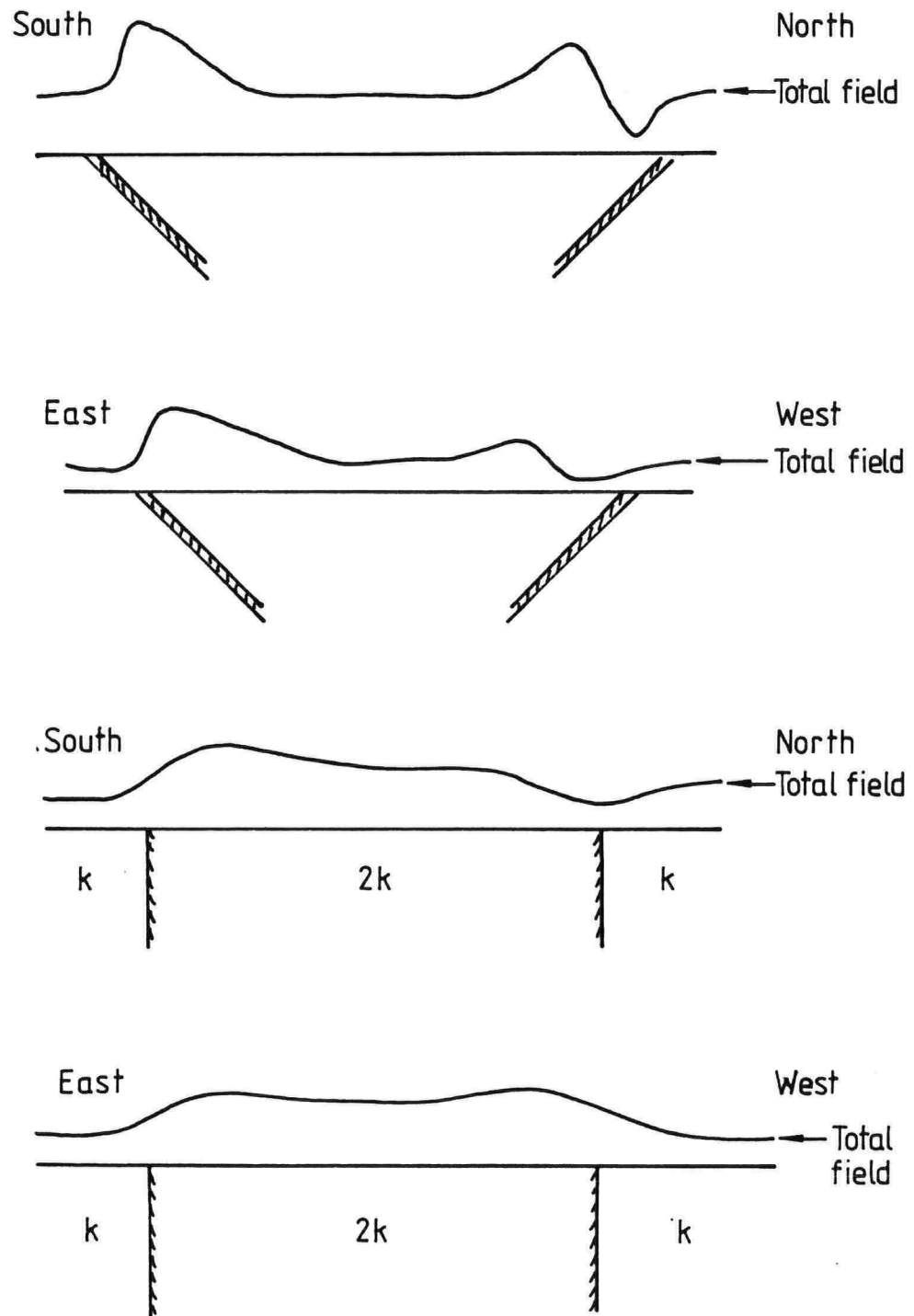
relatively distant so that its effect is ignored) (Breiner, 1973). This condition would not exist in the case of a landfill containing metal. Not only would there be a series of randomly oriented dipoles, but some of the metal may contain a significant permanent magnetisation. The usual interpretation procedures consider only induced magnetisation for simplicity; any permanent magnetisation is usually insignificant unless magnetite or iron is encountered.

Total field anomalies produced by various simple models have been published by Breiner (1973). They are for use as a qualitative guide only. Those applicable to a dipping susceptible dyke, and a fault block or wide dyke are reproduced in Fig. 7.9.

Comparison with the field profiles shows that there is some similarity between the North-South traverses and the model profiles produced by dipping dykes and to a lesser extent with the fault block model. The East-West profiles do not show a good match.

Generally, the results show consistency between traverses. The large anomalies at 8+20m on Line C (Fig 7.1) is also shown on the perpendicular traverses on Lines 8 and 9 (Figs. 7.6 and 7.7) at C.

Magnetic anomalies across fault block  
and dipping dyke, field inclined  $45^\circ$



(from Breiner 1973)

Fig.7.9

#### 7.4 Conclusions

In very general terms, the north-south profiles Figs. 7.1 to 7.8 all show the asymmetric profiles typical of a line of dipoles with the earth's field inclined to the north. They show the characteristic negative and positive peaks at the north and south margins respectively. The landfill appears to be approximating to a large magnetically susceptible body, or a body bounded by dipping sheets.

The presence of metal has been strongly suggested by this and other methods on this site. The method would work if no metal was present. Bricks in particular, in fill, would produce an anomaly (Raybould and Price 1966).

The position of the boundaries would not necessarily be expected to be coincident with the centre of the low point on the magnetic profiles. Inspection of the profiles shows however, that in most cases the boundary is coincident with this point. The variation of the shape of the anomaly profile, depending on the orientation of the source body, makes interpretation ambiguous.

A grid of data points, contoured to reveal the variation in the Total Field would be a useful method of presentation. Characteristic pairs of maxima and minima, signifying dipole sources would be revealed, and thus the location of smaller structures within the fill could be determined if required.

The Proton Precession magnetometer is not a continuous read-out device, although it could be connected to a data recorder. A Flux-gate magnetometer does give a continuous read-out, and would therefore be a suitable alternative. The sensitivity of these instruments is less than the Proton Precession magnetometer, but they have been used successfully to map large areas, when used in conjunction with automatic data recorders (Sowerbutts 1987). The method could be applied with similar success to any landfill containing metal, provided that there is not too much other metal outside the boundaries of the fill.

## 8.0 OTHER METHODS

### 8.1 Ground Penetrating Radar

This technique utilises pulses of high frequency electromagnetic waves (100 to 1000 MHz) which are directed into the ground from an antenna which usually also serves as the receiving antenna. The pulse duration affects the resolution of the survey. A pulse duration of 2ns would detect reflectors of a few cms in size, while a pulse duration of 10ns would detect reflectors of a few metres (Vaughan 1986). Reflections occur at horizons of contrasting dielectric properties. The depth of penetration is affected by the conductivity of the ground and the radar frequency and is usually in the range 1-10m, but 30m is possible in favourable conditions (Leggo 1982, Benson and Glaccum 1979).

Highly conductive ground absorbs the electromagnetic energy, thus reducing the depth of penetration. Generally therefore, wet soil, clay and salt contaminated ground is unlikely to be suitable for a ground penetrating radar survey. Benson et. al. (1983) point out, however, that the technique had been used to profile bottom sediments through ice and water. The application to the delineation of waste tips would appear to be limited. High conductivity is a characteristic of waste and leachate, as shown in the previous chapters. Published work on the application of the technique to waste deposits is limited to the detection of buried waste

containers. Koerner et. al. (1982) found that radar detected plastic and metal drums buried in dry sand, but not in saturated fine grained soil. However, he speculated that a signal enhancement circuit would improve the results in saturated soil. Benson and Glaccum (1979) suggest that the technique could be used to trace pollutants, but do not give any examples. Presumably they intended to indicate that the method should identify pollutants from a negative response in contrast to unpolluted soil.

The depth of reflectors displayed on the record can be determined if the value of the dielectric constant is known, or assumed. The following formula is applied:

$$D = \frac{c \times t}{2 e_r} \quad (\text{Johnson et. al. 1979})$$

where D = depth

c =  $3 \times 10^8$  m/sec = velocity of electromagnetic wave

t = pulse travel time in nano seconds

$e_r$  = dielectric constant

An opportunity arose to run a ground radar traverse and the results are included as an illustration only. The equipment used was a S.I.R.3 manufactured by Geophysical Survey Systems Inc. The survey was run by Structure Testing Services, of Southampton. The site was wet at the time the survey took place after heavy rainfall. A 45m traverse was run on Line F across the western boundary. Three antenna sizes were used; 120 MHz, 300 MHz and 500 MHz.

The results are included in the Appendix. They show the expected poor penetration on the fill material, indicative of absorption by the clay cap. A feature common to all traces is the vertical boundary at grid line 3, which is believed to be the edge of the clay cap, overlapping on to the host material. In general terms, it is clear that the higher frequency record shows a more detailed trace, but the lower frequency recorded has a greater penetration depth. No record shows reflection of structures on the filled area.

The survey was undertaken relatively quickly. The antennae were towed at a slow walking pace. Results were immediately displayed without the need for further data reduction. The method may have produced better results, had the site not been so wet. It would produce better depth penetration on a granular fill site.

## 8.2 Metal Detectors

Metal detectors work on the same principle as very low frequency electromagnetic (VLF-EM). Eddy currents are induced in a metal target by a primary magnetic field. The eddy currents are either sensed by the receiver, or a loading on the transmitter is measured. Any metal object within range of the transmitter will be detected. The response varies with the distance raised to the 6th power and is therefore a shallow depth device (Benson and Glaccum 1980).



Metal detectors have been used to detect buried metal drums; Koerner et. al. (1982), Benson and Glaccum (1980), Benson et. al. (1983). They could be applied to the delineation of waste tip boundaries if the waste contained a high metal content. If used in conjunction with a magnetometer, they would identify non-ferrous metals, as a magnetometer detects only ferrous metals. This combination was used over a hazardous waste burial site by Benson and Glaccum (op. cit.), who were able to identify ferrous metal in this way.

### 8.3 Micro-Gravity Surveys

The introduction of microgravity meters, such as the La Coste and Romberg "microgal" models, has enabled gravity anomalies to be measured to the nearest  $\pm 0.002$  mGals (Kick 1985). The method has been applied to the detection of solution features in Karst terrain. Colley (1963) was able to detect anomalies of 0.5 to 1 mGal which were correlated with solution features, but later Barrows and Fett (1985) were able to map to the nearest 0.1 mGal using a microgravimeter over a Karst region.

It has been suggested by Kick (1985) that the method could be applied to landfill where density contrasts would be expected. The survey stations would have to be accurately levelled, and the usual corrections made for tide and regional gravity variation would be required. It would be a method which should work well on those sites where seismic methods do not as a result of poor energy propagation in

loose fill. Therefore, it should be considered as one of the methods in a reconnaissance survey.

## 9.0 COMPARISON OF METHODS

### 9.1 Resistivity and Electromagnetic Induction (E.M.) Traversing

The most noticeable advantage of the E.M. method over the conventional resistivity traverse method is its speed. On average, it took approximately 15 secs to obtain one set of two orthogonal readings and move to the next station with the EM31 using a station interval of 5m. This compares with about 5 mins to obtain a series of 4 averaged readings and move station with the Terrameter using a 10 m interval. Both times are for a single-man operation. The resistivity readings obviously could have been speeded up with two or three men, which is the normal compliment. Ladwig (1983) claimed that the E.M. technique was four times as fast as conventional resistivity traversing. The EM31 would be cheaper therefore to operate commercially than the conventional resistivity equipment both in terms of time and labour costs.

Both methods suffer the potential disadvantage, common to all electrical methods on landfill and outlined previously, of responding to concentration of leachate which may not necessarily correspond to the boundaries of the landfill

Figs. 9.1 to 9.8 show superimposed plots of the two sets of traverses. Generally the apparent resistivity values derived from the E.M. equipment on the fill are approximately half

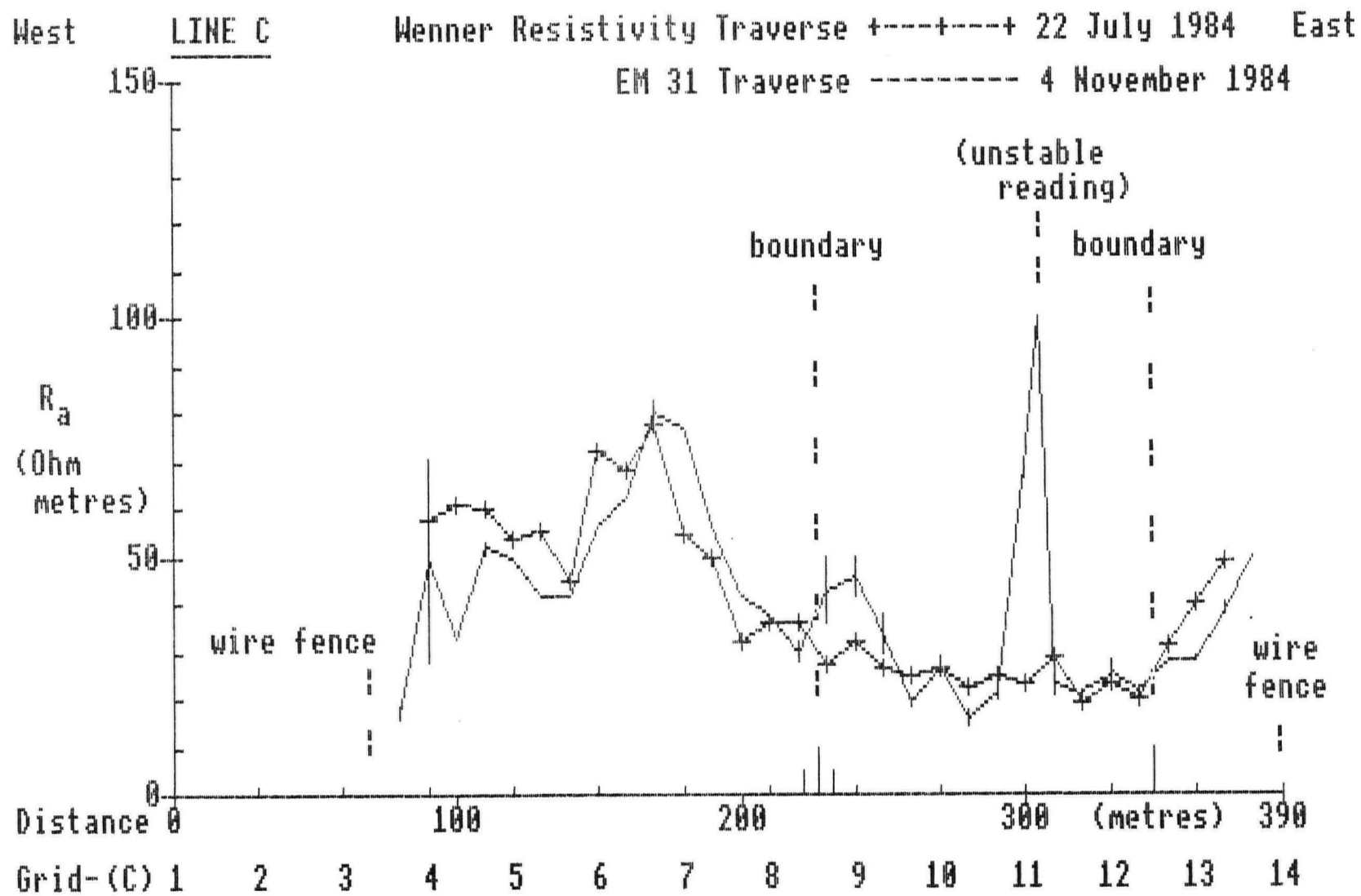


Fig.9.1

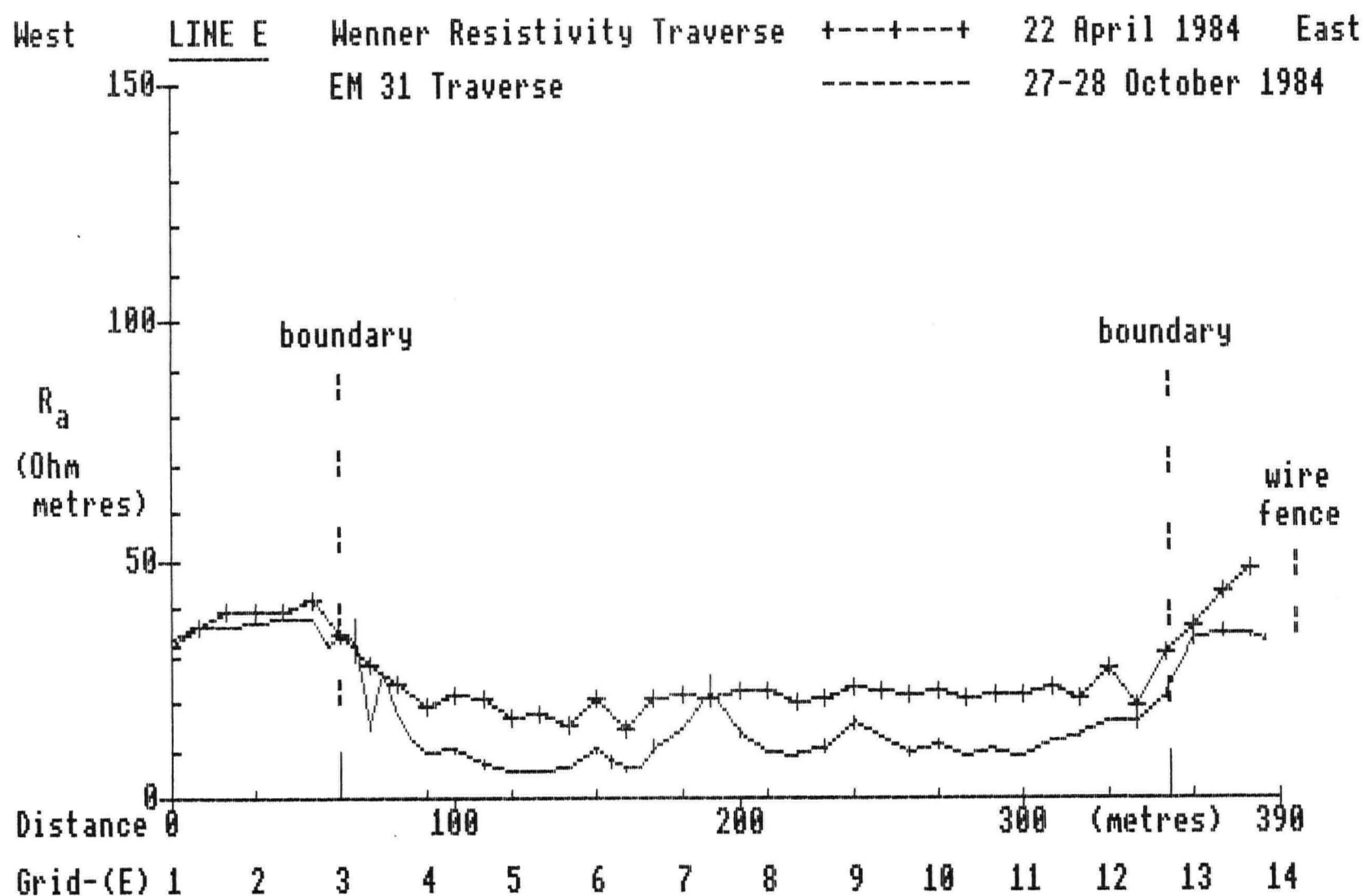


Fig. 9.2

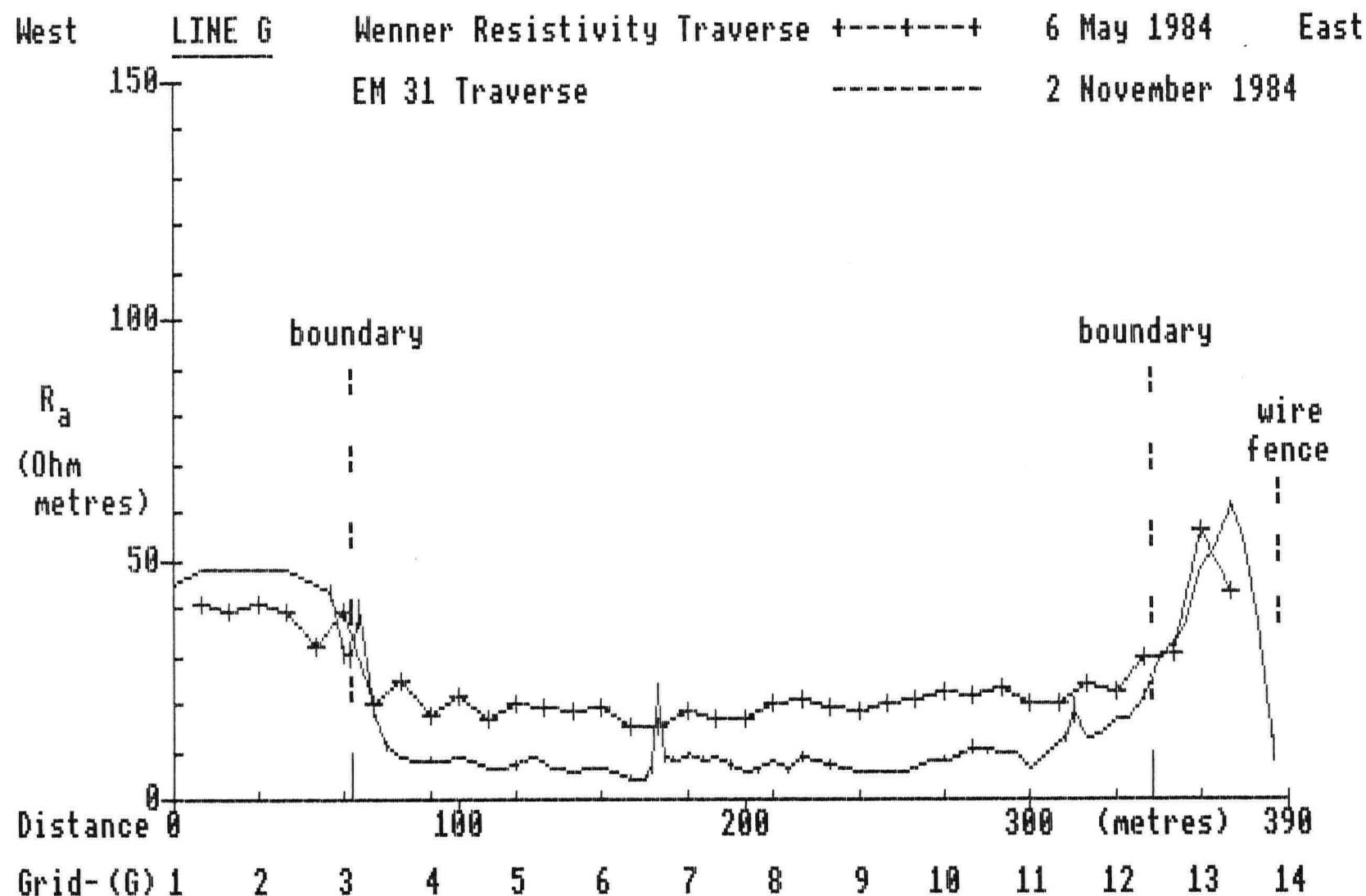


Fig. 9.3

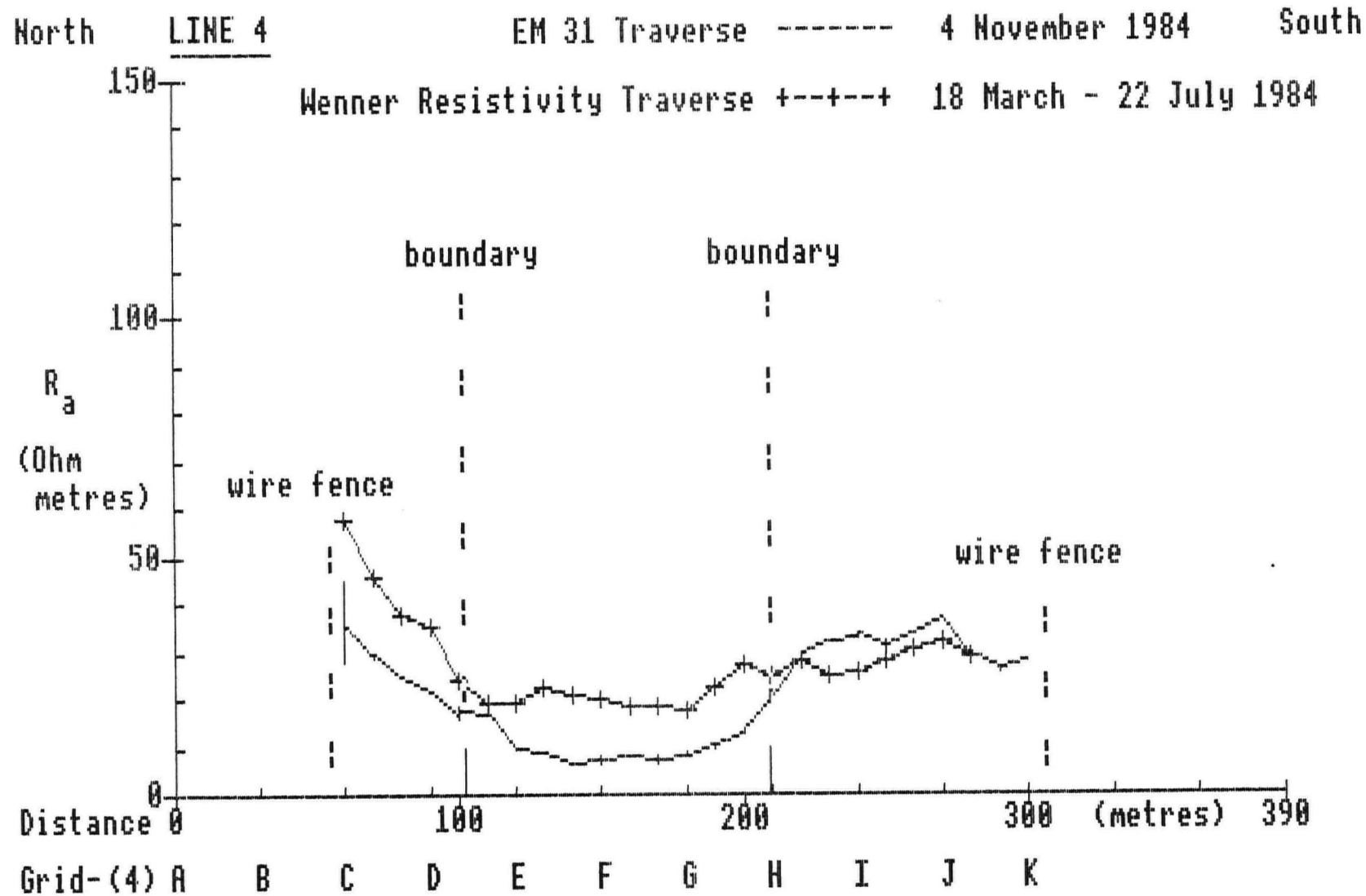


Fig.9.4

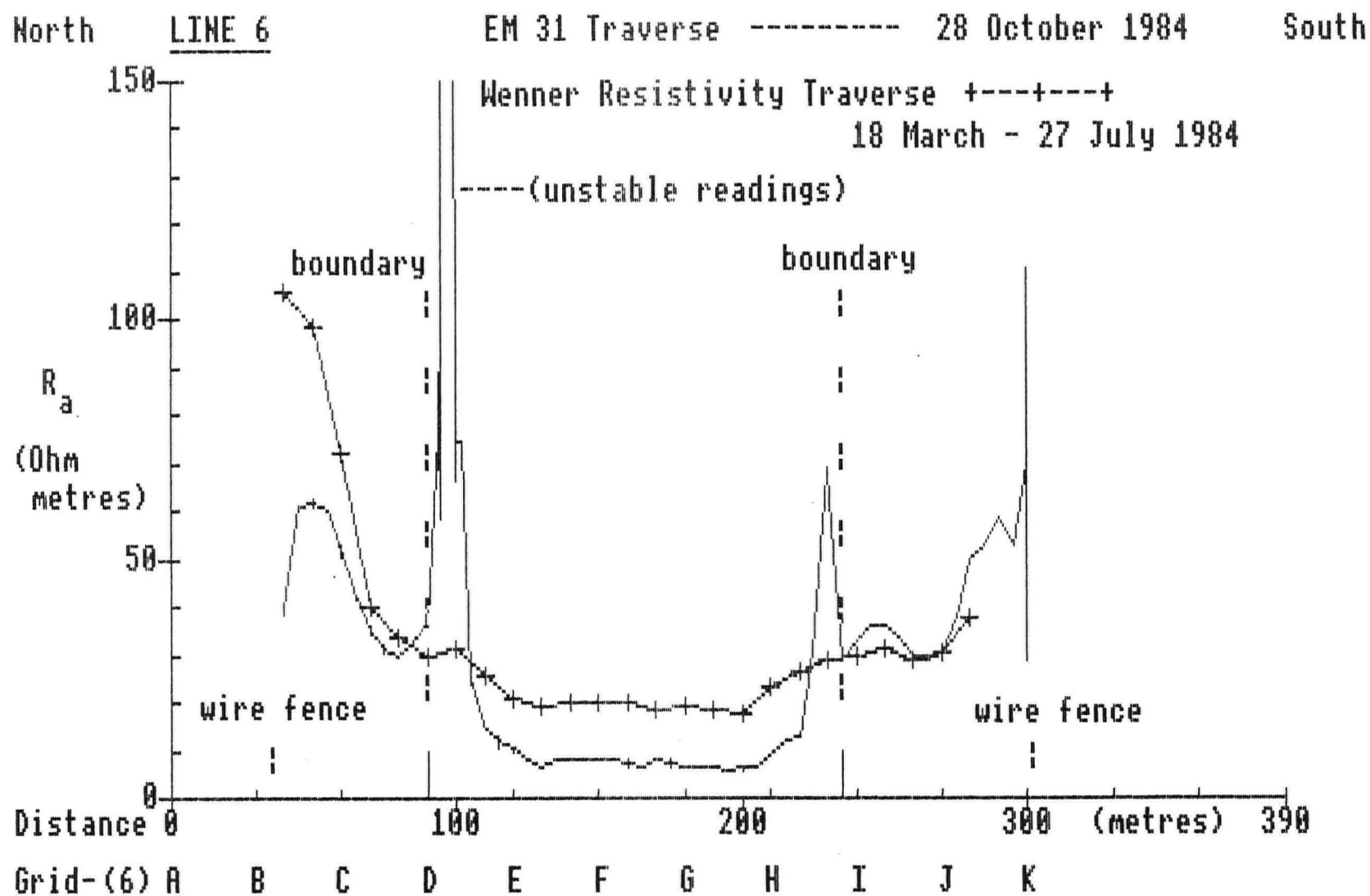


Fig.9.5



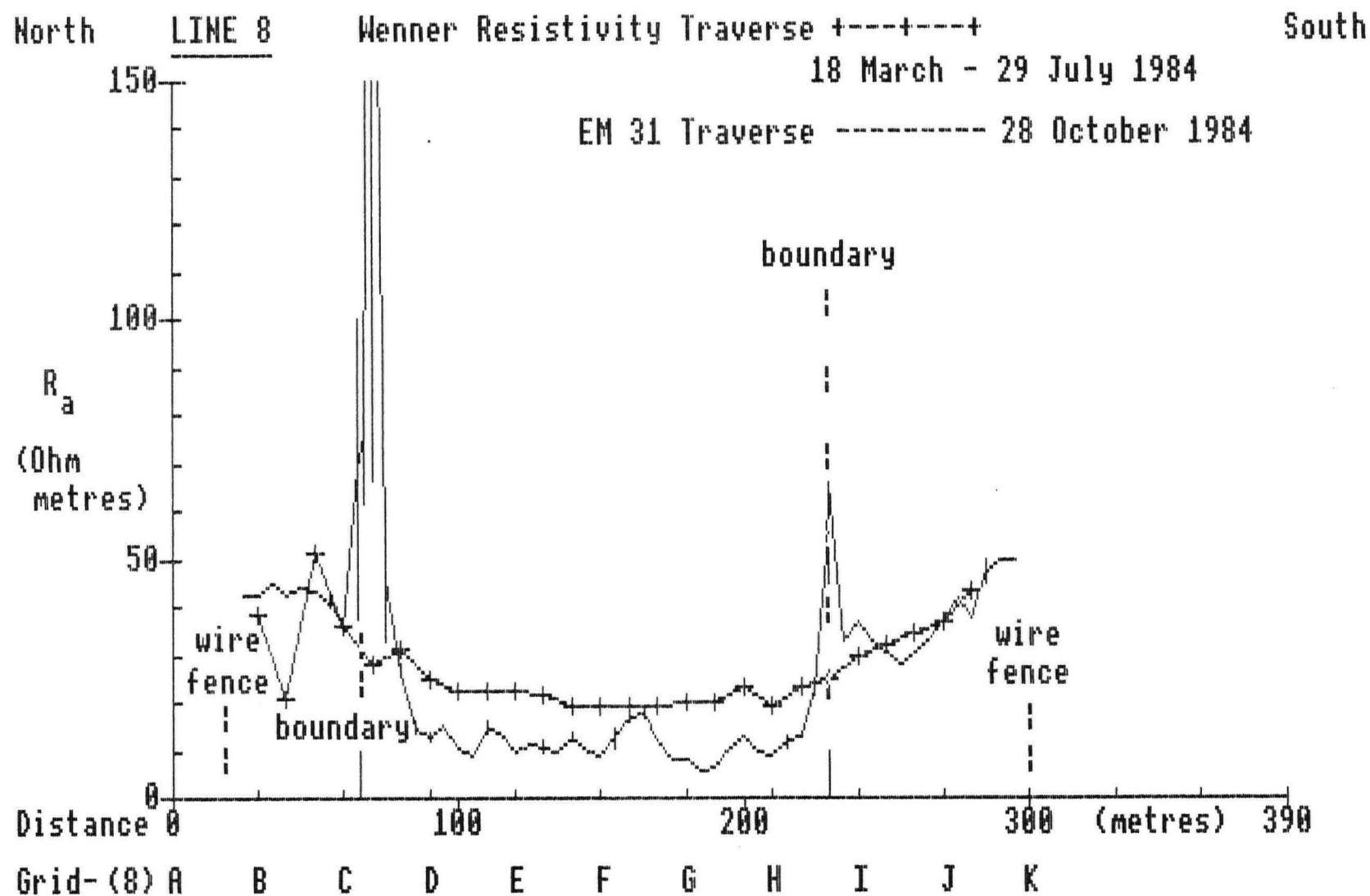


Fig.9.6

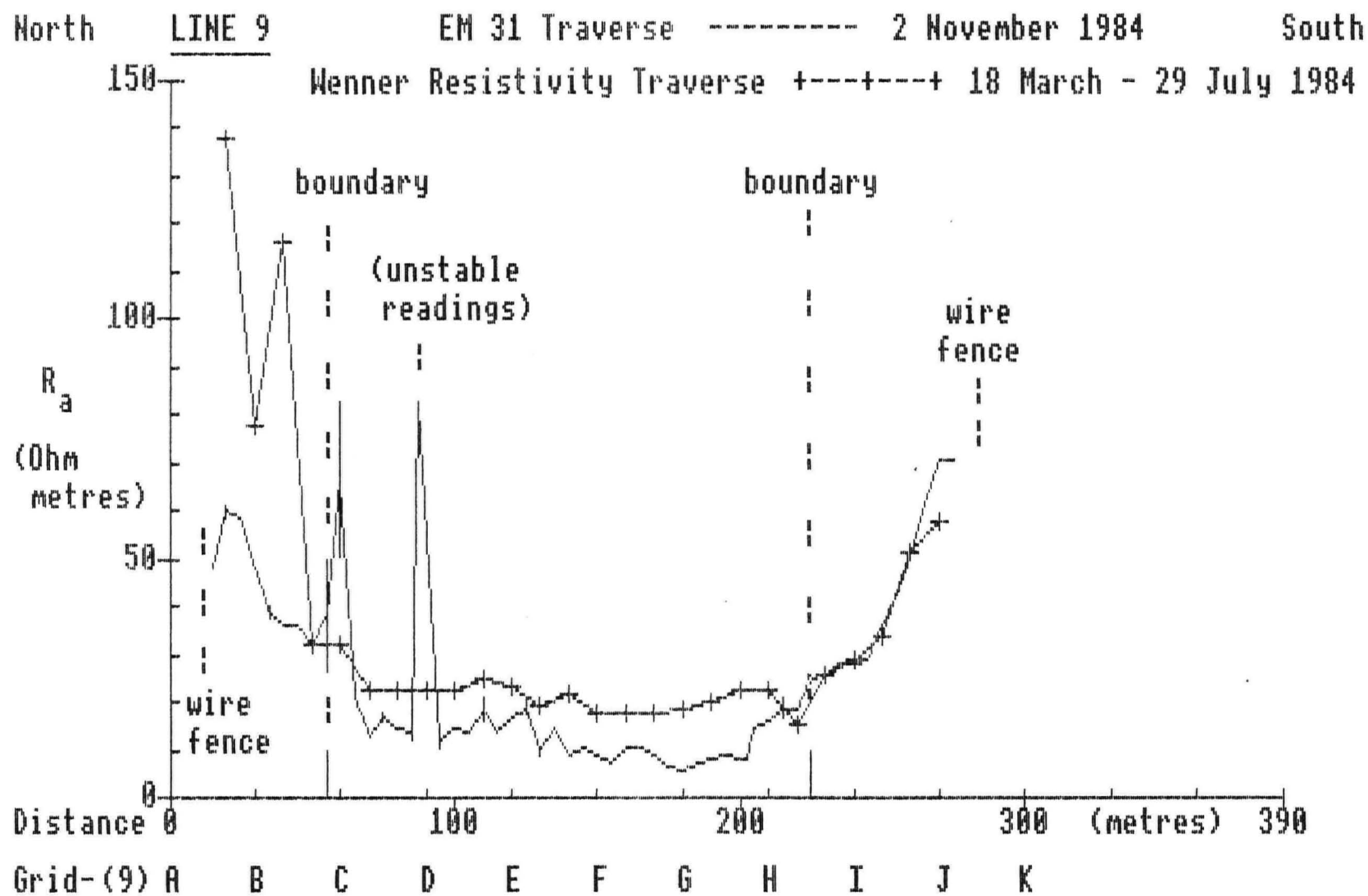


Fig. 9.7

North LINE 11 EM 31 Traverse ----- 28 October 1984 South

Wenner Resistivity Traverse +---+---+ 18 March - 29 July 1984

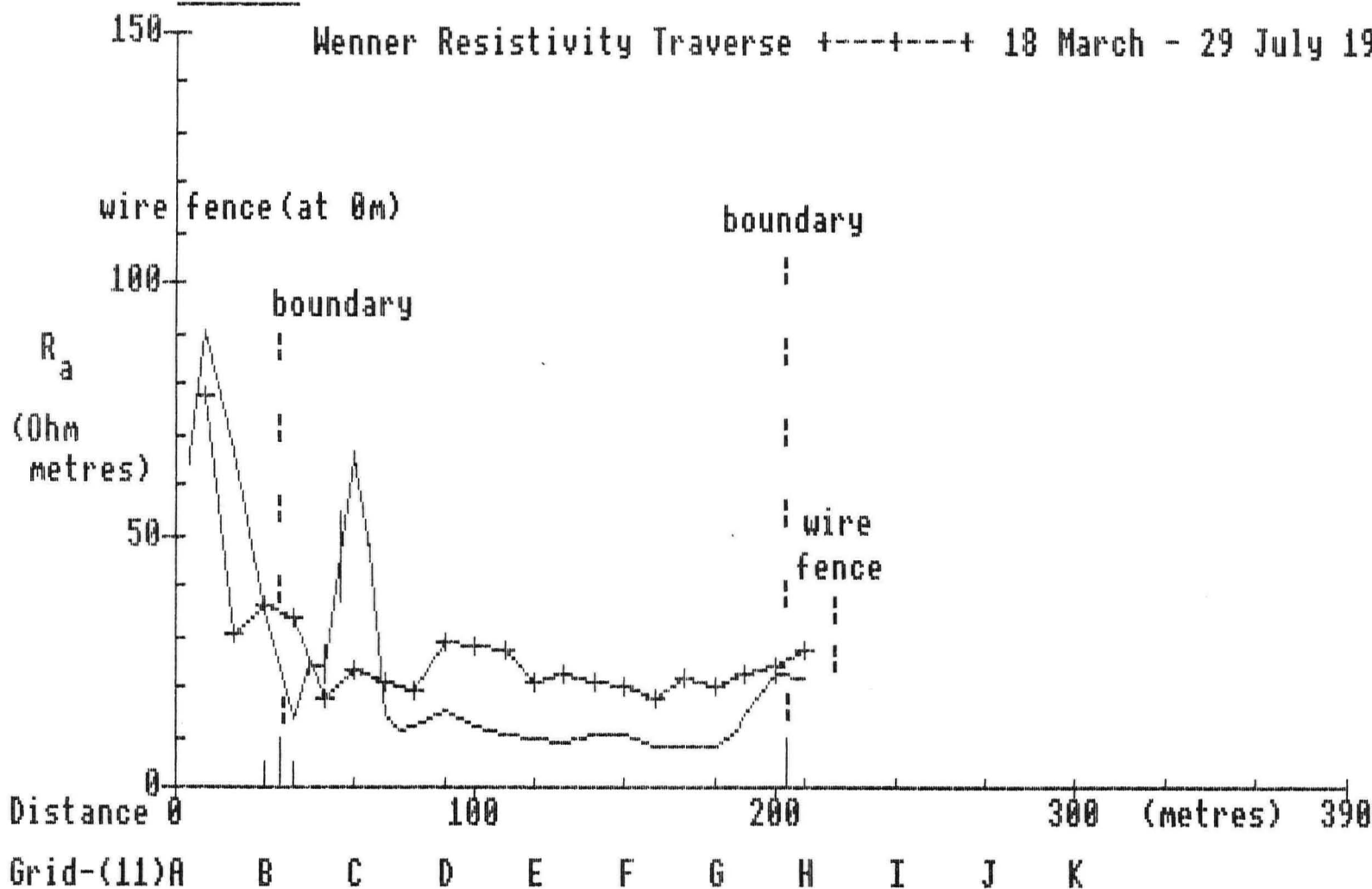


Fig.9.8

those measured using the conventional/resistivity equipment. The E.M. profiles tend to show more irregular peaks on the fill, some of which are associated with unstable measurements. However the north-south E.M. profiles also show peaks at the boundary (see Lines 6, 8, 9 and 11). Even on the east-west profiles the EM31 shows a more distinct change in resistivity across the boundary than the SAS Terrameter.

Off the fill material, the two sets of resistivity data tend to agree, except at the northern ends of Lines 4, 6 and 9, where the Terrameter equipment produces higher readings.

The differences described above can be attributed in part to the difference in depths at which the two sets of instruments operate. The Wenner configuration with an electrode spacing of 10m is influenced by the clay beneath the fill and gravel, as well as the more shallow materials. The EM31 responds to material above approximately 6m, which is predominately the fill and sand and gravel. It is also more affected by shallow buried metal than is the conventional resistivity instrument. The closer station interval used on the E.M. traverses will also have contributed to the more complex profile.

The measurements obtained with the conventional resistivity array may also be expected to give higher resistivity values than the E.M. equipment because the former was partly carried out during a dry summer (March to July 1984) and the E.M. survey was carried out during early winter (November

1984). The ground moisture content would have differed between the two survey dates, probably sufficiently to affect the results. The northern part of the site was surveyed last on the resistivity survey (in July) and this is where the higher resistivity is most marked (see Lines 4, 6 and 9).

The superimposed E.M. and resistivity profiles do not show a suspiciously high E.M. resistivity profile (except at the boundaries) which might be attributable to that instrument's non-linear measurements at low resistivities. This is at variance with the findings of Glaccum et. al. (1983) and was discussed in section 5.1.

Figs. 4.17a and 5.11 show a small part of the northern boundary with resistivity contours plotted at 10 ohmm intervals. The former was surveyed with the conventional resistivity equipment and the latter with the E.M. equipment.

It is clear from the two contoured plans that there is little similarity between the two survey results. The differences could be due to the different measurement methods used for the two surveys as outlined previously. The resistivity survey employed a colinear electrode array without additional readings obtained with the electrodes arranged perpendicularly to the first set. The electromagnetic survey employed two mutually perpendicular sets of readings. However, the second set of readings in the E.M. survey only alters the result where there is high apparent

resistivity; elsewhere there is very little difference between the two sets of values. The values on the two contour plans are of the same order, except at the 'resistivity' highs.

The depth of penetration of the resistivity equipment is greater than the E.M. The contour pattern produced from the electromagnetic results is more "peaky", which suggests that shallow depth anomalies are being represented (this is shown clearly on the individual traverse profiles).

The effect of the wire fence is shown on the electromagnetic contour plan, as would be expected. The resistivity values on the north west corner, adjacent to the fence, are low, whereas on the conventional resistivity survey, there is a resistivity high at this point. The wire fence seems to have had the effect of swamping the electromagnetic resistivity measurements on the north west corner so that it may have obscured the trough feature shown on the conventional resistivity contour plan.

The definition of the boundary position is better on the E.M. traverses than on the resistivity traverses. This is partly due to the greater contrast produced by the E.M. equipment. This is particularly noticeable on Line 4, which produced a poor result from the conventional resistivity method at the southern end. The other north-south E.M. traverses show peaks at the boundaries, but this is likely to be produced by metal, as previously stated, and does not represent a characteristic of the ground at the boundary.

These peaks tend to mask the true resistivity trend and where the gradient between fill and host material is low, for example Line C, the definition of the boundary is worse than on the resistivity traverse.

## 9.2 Magnetometer and E.M.

The Proton Precession magnetometer provides information quickly. On average it took half a minute to obtain the three readings at each station and to move to the next station, using a station interval of 5 metres. One-man operation was possible.

The magnetometer traverses have produced profiles which strongly suggest the presence of ferrous metal. The E.M. results, whilst indicative of metal, do not specifically indicate ferrous metal. The size of some of the anomalies, in particular 2000 gammas at grid 9C (Fig. 7.1, Line C and Fig. 7.8, Line 9) indicate a high degree of permanent magnetism.

The E.M. profiles in some places show a difference between the two perpendicular readings, where the magnetometer survey does not show an anomaly. For example, at grid 4C on Line C (Fig. 9.1) and Line 4 (Fig. 9.4)) or grid 6K on Line 6 (Fig. 9.5). These appear to be associated with close proximity to the wire perimeter fence. This fence does not affect the corresponding magnetometer traverses (Figs. 7.1 and 7.4 or 7.5). The EM31 manual states that the instrument

is relatively unaffected by fences, overhead power lines and nearby metallic objects.

The EM31 will produce rapid variations at the junction of two materials of greatly contrasting conductivity which the Operator's Manual calls "edge effects". Similarly the manual states these may be produced by very good conductors which have dimensions of the order of the intercoil spacing (3.66m). Reference to a magnetometer traverse at the positions of suspected conductivity contrasts would help distinguish such contrasts from another alternative source which is ferrous metal (but not from non-ferrous metal). An example of a rapid variation in response produced by a high conductivity contrast may be the reading obtained at grid 11C (Fig. 5.1, Line C, or Fig. 5.8, Line 11). There is no corresponding anomaly on the magnetometer traverse (Figs. 7.1 and 7.9).

### 9.3 Other Methods

The speed of survey using the S.P. equipment was intermediate between the resistivity traversing and the non ground contact methods. Readings were usually stable within half an minute, but removal of turves took a little time. The method could be used by one man, but two would be quicker. The cost of the equipment is relatively cheap, comprising only non-polarising electrodes and a high impedance voltmeter.



The relatively large magnetic anomalies indicative of metal in the fill shows that S.P. anomalies measured are likely to arise from corrosion potentials. The S.P. traverses all produced peaks at the fill/host boundary, which suggests that metal is present here, as has been suggested by the E.M. and magnetometer surveys. However, electrochemical concentration gradients may also be responsible for some of the S.P. anomalies at the boundaries.

The seismic refraction survey was the most expensive in terms of time, labour (and cost of equipment). The results were potentially the most useful in so far as a successful interpretation would have revealed the depth of the fill and the dip and position of the boundary.

The data that was obtained did not enable a quantitative interpretation of depth on the fill side of the boundary and therefore the method was inefficient in terms of time taken and amount of information obtained.

#### 9.4 Comparative Information on the Site

The assumed boundary position at the southern end of Line 6 appears to have been wrongly positioned on the traverses. Both the seismic refraction and EM31 traverse suggest that it should be located 6m further north. This is further corroborated by the corresponding magnetometer traverse (see Figs. 3.2, 5.5 and 7.5). The resolution of the Wenner resistivity traverse is not sufficient to allow it to be

used to the accuracy required to determine the boundary position to within 6m.

The E.M. profile across 9C, Figs 9.1 and 9.7 (Line C and Line 9) show a larger than normal difference between the two mutually perpendicular readings, which is characteristic of the effect produced by shallow metal conductors (EM31 Operating Manual). An erroneously high resistivity is also a characteristic response to metal. A similar result is produced on Line 9 at D (Fig. 9.7). This particular high E.M. derived resistivity peak coincides with the unusually low resistivity measurement displayed on the apparent resistivity space section (Fig. 4.28). There is no coincidence between the results from the two methods at 9C. It can be inferred therefore that the source at 9C is shallow, affecting only the E.M. results, whereas the source at 9D is deeper, affecting both the E.M. and the conventional resistivity results.

The narrow width of the magnetic anomaly at 9C (Line C, Fig. 7.1 and Line 9, Fig. 7.8) also tends to indicate that the source at 9C is shallow.

The northern parts of the magnetometer traverse on Lines 8, 9 and 11 near grid Line C, all produce large anomalies near the host/fill boundary, thus the main anomaly at 9C has extensions east and west.

Comparison of the magnetic anomalies with the corresponding resistivity and E.M. profiles on Lines 8, 9 and 11 again

indicates a shallow source. There is little perturbation of the resistivity traverse and the E.M. profiles show the characteristic difference between the two sets of readings (Figs. 9.6, 9.7 and 9.8).

The resistivity soundings, the resistivity and E.M. traverses and the apparent resistivity space sections tend to indicate that the fill is wedge-shaped, tapering to the south.

The magnetic anomalies and the E.M. profiles can be interpreted as indicating a dipping sheet conductor at the boundaries. The explanation for this may be a concentration of metal on the base and sides of the fill.

10.        RECOMMENDATIONS FOR THE DEPLOYMENT OF GEOPHYSICAL  
            METHODS ON LANDFILL

If the existence of landfill is suspected on a site, but its position and extent is not certain, a rapid reconnaissance using geophysics would be more productive than a series of trial holes or boreholes. Appropriate methods for the type of landfill, studied at Panshanger are magnetometer and electromagnetic induction traversing. The variable station interval method should be employed and the positions of rapid changes in readings pegged out whilst traversing.

The boundary should then be confirmed by trial pitting or a series of shallow borehole traverses.

The results from the Panshanger landfill have shown that for this combination of fill and host material the depth of the fill should be determined by borehole drilling. The extent to which geophysical methods could be employed to interpolate depths between boreholes depends on the resistivity contrasts and the state of compaction of the fill. At Panshanger both conditions were unfavourable, but this would not necessarily be the case on other similarly contained landfills. The use of resistivity soundings and seismic refraction should be considered for interpolation of depths between boreholes.

If the existence of landfill is known, together with the approximate position of the boundary, a trial pit and

borehole survey to confirm the boundary and depths should be undertaken initially. Geophysical methods could then be used to interpolate the boundary (and depths if a suitable contrast exists).

The production of leachate is a peculiarity of landfill and therefore electrical methods should be of prime consideration in most combinations of fill material and host material. As far as possible two methods utilising different ground parameters should be employed, for example seismic and resistivity. This would provide a mutual validation of the results, and in particular a check on the validity of results from electrical methods which are prone to distortion from the effect of leachate migration.

Where electrical methods fail due to lack of contrast or the masking effect of leachate, a combination of seismic refraction and microgravity surveys may be successful.

## 11.0 SUMMARY OF CONCLUSIONS

### 11.1 Location of Boundaries

All the traversing methods tried on the site at Panshanger located the boundaries of the fill at or near to the surface. The seismic refraction method located the boundary if the shot was fired on the host material.

The properties measured which provided the contrast displayed on the traverses were electrical conductivity, and the amount of metal contained. The two best methods in terms of speed, flexibility of location, and accuracy of the result, were E.M. traversing and geomagnetic traversing, the former utilising electrical conductivity and the latter utilising metal content to provide the contrast. These methods are recommended as the cheapest and quickest, and suitable for a first reconnaissance survey.

The contrast provided by the metal content of a fill is a more or less fixed parameter characteristic of that particular fill. It is independant of the properties of the host material or groundwater regime. Therefore any fill which contains ferrous metal could be detected using geomagnetic traversing and its boundaries delineated. Metal detectors would respond to ferrous and non-ferrous metal and could supplement the magnetometer to provide further information (Benson and Glaccum, 1980).

The conductivity/resistivity contrast between a fill and its host material is dependant upon the nature of the host material and on the groundwater conditions. The site at Panshanger was favourable to the production of a good contrast on the traverses in both respects; the resistivity of the sand and gravel, and the fill was dissimilar and there was apparently little groundwater.

However, if the host material had been clay, there would not have been a sufficient resistivity contrast on the traverses. (This was also demonstrated at Panshanger by the poor resistivity depth probe interpretation of the boundary between the fill and basal clay.) Similarly, if there had been a water table within the sand and gravel, its resistivity would have been reduced, thus reducing the contrast measured at the boundary. If there had been groundwater flow through the fill, with a leaky landfill, the production of leachate may have masked the physical boundary, a problem highlighted indirectly by Cartwright and McComas (1968) and Klefstad et al (1975).

The use of E.M. or resistivity traversing will not necessarily produce results which can be used to detect the boundaries of all landfills.

It is suggested that the anomalies produced by the S.P. traversing method are partly a result of metal oxidisation potentials. To the extent that this is the case, this method would work as well on other landfills containing metal, regardless of the nature of the host material. That

part of the S.P. anomaly which is produced by electro-mechanical concentration gradients would be somewhat site-dependant. The method generally is not recommended as a reconnaissance tool, but others have suggested its use as a monitoring method (Markiewicz 1984).

#### 11.2 Determination of the Depth of Fill and Dip of the Host/Fill Boundary

Quantitative interpretation of the depth of the fill and of the dip of the host/fill boundary was less successful at Panshanger. The interpretation of resistivity depth probes suffered from lack of resistivity contrast between the fill and basal clay. Similar problems were encountered by Knight et. al. (1978) and Nunn (1979). The value of resistivity of the fill (and the clay) was in the range of 9-28 ohm m, which is in agreement with the range of values measured for fill by the previously quoted authors.

An indication of the dip of the host/fill boundary can be obtained from use of the "abbreviated mapping system" of Habberjam and Jackson (1971) applied to square array traverses. An impression of the dip also can be obtained by constructing apparent resistivity space sections. These cannot be interpreted unless the boundary approaches that of an infinitely dipping interface, with respect to the electrode spacing. The fill at Panshanger was too shallow to allow such interpretation, but deeper filled areas would provide the necessary conditions. (If the other conditions



required for the satisfactory interpretation of electrical methods, outlined above, are met.)

A successful application and interpretation of the seismic refraction would provide the depth of fill and the dip of the host/fill boundary. Unfortunately the fill at Panshanger was too energy absorbing to allow sufficient propagation of P waves using the shot source available. Explosives were not permitted on this site (because of the livestock), but there is some evidence that a more successful result may have been achieved if a buried explosive source had been used (Knight et. al. 1978, Smith, personal communication).

Fills which are less energy absorbing would produce better seismic results. Nunn (1979) used seismic refraction on a fill containing a mixture of domestic refuse and colliery spoil with more success than at Panshanger.

Ground penetrating radar was not successful at Panshanger, but on a drier landfill with less clay, its use should be considered. It is capable of producing results which can be interpreted to give depth of fill and dip of the boundary, provided the dielectric contrasts are known.

### 11.3 Recommendations

The most suitable instruments to use on this type of site, and others, for a preliminary reconnaissance are the electromagnetic conductivity meter (EM31) and the Proton Precession magnetometer or fluxgate magnetometer (both instruments are also widely available for hire or purchase relatively cheaply). More detailed information on depths and dips could be obtained on suitable sites from seismic refraction, ground radar and apparent resistivity space sections.

The examples cited from the Literature and the trials performed at Panshanger have shown that the amount of excavation necessary in an investigation of a landfill can be reduced by using the appropriate combination of geophysical methods. This can be of particular importance, from the health and safety aspect, on many landfills which will contain pathogens, toxins, or other hazardous waste.

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## APPENDICES

1. Photograph plates
  1. North West corner - view towards North East  
South West corner - view towards South East
  2. Southern boundary - view towards West  
Eastern boundary - view towards North
  3. Northern boundary - view towards West
2. Borehole vertical graphic sections 6F,  
9+24m, B+19.5m, 2F
3. Ground Radar print-out

Panshanger Landfill



North West corner - view towards North East



South West corner - view towards South East

Panshanger Landfill



Southern boundary-view towards West



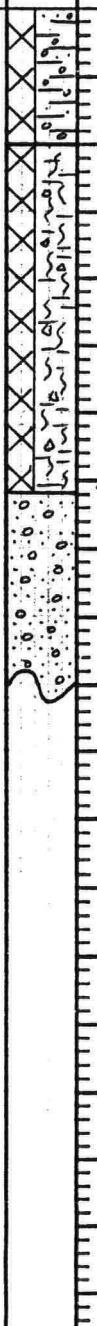
Eastern boundary - view towards North

Panshanger Landfill



Northern boundary - view towards West

				Borehole No. 6F			
				Sheet 1 of 1			
Equipment & Methods Cable-tool percussion rig 200 mm. diameter			Location No. Panshanger Land fill				
Carried out for			Ground Level 16.46 m.		Coordinates		Date 10.6.85
Description	Reduced Level	Legend	Depth & Thickness	Samples/Tests			Field Records
				Depth	Sample Type	Sample No.	
Firm to stiff brown silty, sandy, gravelly, CLAY Firm brown/grey sandy CLAY with small - medium GRAVEL, + brick, clinker, wood. - becoming moist with inclusions of black fibrous refuse. ("clay" cap)	16.16		0.3				
	15.86		0.6				
	15.56		0.9				
Compressible partly decayed REFUSE comprising - approx. 50% paper, card, wood; 25% glass, plastic, metal/wire; 25% moist black cohesive fine-grained matrix. (compressed paper still readable - envelope post-marked December 1969.)				1.0-1.45			S "N" = 11 (suspect too high see below)  slow progress due to tool bouncing
- as above but wet. (base of fill at 4.1m)	12.46		4.0				W.S. 
	12.36		4.1				
Stiff brown sandy, and grey CLAY with small to medium sub-rounded chalk gravel and a little medium to large angular flint gravel. (till)							
(drilling terminated at 5.6m)	10.86		5.6				
SPT Where full 0.3m penetration has not been achieved the number of blows for the quoted penetration is given (not N value).  Depths: All depths and reduced levels in metres. Thicknesses given in brackets in depth column.  Water: Water level observations during boring are given on last sheet of log.			Sample/Test Key D Disturbed Sample B Bulk Sample W Water Sample   Piston (P) Tube (U) or core sample. Length to scale S Standard Penetration Test V Vane Test C Core recovery (%) r Rock Quality Designation (RQD %)			Remarks water strike at 4m.	
					Logged by A.R.C.		
					Scale		
					Fig.		

				Borehole No. 9+24m,B+19.5m			
				Sheet 1 of 1			
Equipment & Methods Cable-tool percussion rig 200 mm. diameter			Location No. Panshanger Landfill				
Carried out for			Ground Level		Coordinates		Date 10.6.85.
Description	Reduced Level	Legend	Depth & Thickness	Samples/Tests			Field Records
				Depth	Sample Type	Test No.	
Firm brown CLAY and medium to large GRAVEL ("clay"cap)			0.5				
Compressible decayed REFUSE with plastic sheeting.			1.8				
Medium dense, orange brown SAND and small to large, sub-rounded GRAVEL.			2.5				
(drilling terminated at 2.5m)							
<p><b>SPT</b> Where full 0.3m penetration has not been achieved the number of blows for the quoted penetration is given (not N value).</p> <p><b>Depths</b> All depths and reduced levels in metres. Thicknesses given in brackets in depth column.</p> <p><b>Water</b> Water level observations during boring are given on last sheet of log.</p>			<p><b>Sample/Test Key</b></p> <p>D Disturbed Sample</p> <p>B Bulk Sample</p> <p>W Water Sample</p> <p>  Piston (P) Tube (U) or core sample Length to scale</p> <p>S Standard Penetration Test</p> <p>V Vane Test</p> <p>C Core recovery (%)</p> <p>r Rock Quality Designation (RQD %)</p>			<p><b>Remarks</b> hole dry</p>	
							<p>Logged by A.R.C.</p>
							<p>Scale</p>
							<p>Fig.</p>

				Borehole No. 2F			
				Sheet 1 of 1			
Equipment & Methods Cable-tool percussion rig 200mm. diameter		Location No. Panshanger Landfill					
Carried out for		Ground Level 15.43m.		Coordinates		Date 10.6.85	
Description	Reduced Level	Legend	Depth & Thickness	Samples/Tests			Field Records
				Depth	Sample Type	Test No.	
Topsoil over - dark brown silty SAND and medium to large sub-rounded GRAVEL	15.03		0.4				
Medium dense orange-brown SAND and small to large, angular to sub-rounded, GRAVEL, with bands of clayey sand and gravel near top.	14.13		1.3				
SAND, with a little small gravel.	13.93		1.5				
Stiff brown/grey mottled slighty sandy CLAY, with traces of small angular gravel.	13.63		1.8				
Stiff brown/grey CLAY with small rounded chalk gravel.							
(till)							
(drilling terminated at 2.8m)	12.63		2.8				
<p><b>SPT</b> Where full 0.3m penetration has not been achieved the number of blows for the quoted penetration is given (not N value).</p> <p><b>Depths:</b> All depths and reduced levels in metres. Thicknesses given in brackets in depth column.</p> <p><b>Water:</b> Water level observations during boring are given on last sheet of log</p>		<p><b>Sample/Test Key</b></p> <p>D Disturbed Sample</p> <p>B Bulk Sample</p> <p>W Water Sample</p> <p>  Piston (P) Tube (U) or core sample: Length to scale</p> <p>S Standard Penetration Test</p> <p>V Vane Test</p> <p>C Core recovery (%)</p> <p>r Rock Quality Designation (RQD %)</p>		<p>Remarks hole dry</p>			<p>Logged by A.R.C.</p> <p>Scale</p> <p>Fig.</p>